

Climate Change Impact, Adaptation and Mitigation in Agriculture: Methodology for Assessment and Application

Editors

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The Indian Agricultural Research Institute (IARI) is the premier national institute of the Indian Council of Agricultural Research for agriculture research, education and extension. Established in 1905, IARI is based in the capital city of New Delhi. The Institute is engaged in climate change research for last 20 years. The focus of IARI's climate change research has been to quantify the sensitivities of current food production systems to different scenarios of climatic change, develop the inventory of greenhouse gas emissions from Indian agriculture, identify options for greenhouse gas mitigation, determine the available management and genetic adaptation strategies for climatic change and climatic variability, develop policy options for implementing mitigation and adaptation strategies and provide policy support for the international negotiations on global climate change.

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FOREWORD

Increased concentration of greenhouse gases (GHGs) in the atmosphere resulted in warming of the global climate system by 0.74 °C between 1906 and 2005. The trends of rise in temperature, heat waves, droughts and floods, and sea level shown by the Indian scientists are in line with the Inter-Governmental Panel on Climate Change (IPCC) though magnitude of changes could differ. The mean temperature in India is projected to increase up to 1.7 °C in *kharif* (July to October) and upto 3.2 °C during *rabi* (November to March) season, while the mean rainfall is expected to increase by 10% by 2070. The cases of ravaging and recurrent floods in the north-eastern states during 2002, 2003 and 2004; a record 944 mm of rainfall in a day in Mumbai during 2005 incurring loss of Rs 1000 crore and 1000 lives; devastating floods in Surat, Barmer and Srinagar during the monsoon season of 2006, the droughts in 2000 and 2002, which affected nearly 11 million people in Orissa and the drought of 2006 in north-east which left the people in peril, amply indicate the climatic anomalies. During 2009, the late arrival of monsoon and erratic rainfall later affected rice cultivation in over 5.7 million hectares and 262 districts were declared as drought affected. The western Uttar Pradesh was the worst to be affected with 68 per cent shortage in rainfall. In 2010, when north India received a very good amount of monsoon rain, the eastern part of the country (Bihar, Jharkhand and West Bengal) faced a severe drought. The year 2010 has also been the hottest year ever since the temperature measurement started. The increasing temperature, deficit in rainfall and occurrence of droughts particularly in non-conventional pockets are evidences of weather aberrations indicating climatic risks.

Agriculture, particularly in India with nearly 60% rainfed area, has been a highly risky venture with vagaries of monsoon besides the interplay of other abiotic and biotic factors. Climate change is set to compound the daunting complex challenges already being faced by agriculture. Therefore, concerted efforts are required for mitigation and adaptation to reduce the vulnerability of Indian agriculture to the adverse impacts of climate change and making it more resilient.

However, there are lot of uncertainties about the assessment of impact, adaptation and mitigation of climate change in agriculture. There is a need to develop and apply a standard methodology across the board for various studies related to climate change and agriculture. This book edited by H Pathak, PK Aggarwal and SD Singh of the Division of Environmental Sciences, Indian Agricultural Research Institute is, therefore, very timely and a welcome addition. The book

comprehensively presents the recent, internationally accepted, standard methodologies for studying the impacts of climate change on agriculture, measuring and developing inventories of greenhouse gas emission, and analyzing the vulnerabilities and mitigation options. It describes the methodology in a simple and lucid way so that a researcher can adopt it in laboratory and field studies. Individual chapters are dedicated to different subjects. Through inclusion of case studies and presentation of illustrations, effort has been made to make each chapter easy to understand and follow in the laboratory/field studies.

The efforts put by editors as well as authors in compiling and presenting the available information lucidly in this book deserve appreciation. I sincerely hope that this book will be very useful for the students and researchers working in the field of global climate change and agriculture.



(A.K. Singh)

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PREFACE

Climatic changes and increasing climatic variability are likely to aggravate the problem of future food security by exerting pressure on agriculture. However, there are lot of uncertainties about the assessment of impact, adaptation and mitigation of climate change in agriculture. It is largely because the methodology followed for such assessments is not standardized and sometimes it is inaccurate and imprecise. Researchers follow different methodologies and arrive at contrasting results making it difficult to reach a logical conclusion and develop policy actions. There is a need to develop and apply a standard methodology across the board for various studies related to climate change and agriculture.

This is probably the first book to comprehensively present the recent, internationally accepted, standard methodologies for studying the impacts of climate change on agriculture, measuring and developing inventories of greenhouse gas emission, and analyzing the vulnerabilities and mitigation options. The book describes the methodology in a simple and lucid way so that a researcher can adopt it in laboratory and field studies. Individual chapters are dedicated to subjects such as quantification of climate change impacts on crops in controlled and field conditions, impacts of climate change on water resources, soil fertility, erosion and carbon sequestration, insects, pests, weeds, microbes and diseases; greenhouse gas emission assessment, assessment of regional vulnerability to climate change, selection of crop and vegetable genotypes for climate change adaptation and mitigation, assessing biochemical traits of crops for climate change adaptation and mitigation and assessing the potential of biochar for C sequestration and residue management. With each methodology a case study has been presented illustrating the steps to be followed to achieve the objectives. Efforts have been made to provide example of real case studies. The analysis and application of the results are also illustrated. I compliment the authors of various chapters and editors of this book for their meticulous contributions. I am sure this book will prove an invaluable source reference for the researchers, scientists and students engaged in climate change research.



(H.S. Gupta)

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We sincerely hope that this book will contribute towards a better understanding of the climate change processes, generating accurate data on greenhouse gas emission and impact of climate change using standard methodologies and develop strategies for mitigation and adaptation in agriculture.

New Delhi
March 2012

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ABBREVIATIONS

2, 4-D	2, 4-Dichlorophenoxyacetic acid
ABA	Abscicis acid
ACC	1-Aminocyclopropane-1-carboxylic acid
AMI	Agronomic management index
APX	Ascorbate peroxidase
ARA	Acetylene reduction assay
BC	Bamboo charcoal
BD	Bulk density
BLASTSIM	Model for simulation of blast disease
BNF	Biological nitrogen fixation
BSA	Bovine serum albumin
BYDV	Barley yellow dwarf virus
CAT	Catalase
CDPKs	Calcium-dependent protein kinases
CEC	Cation exchange capacity
CEE	Carbon equivalent emission
CEF	Controlled-environment facility
CERES-Rice	Crop Growth Model
CF	Continuously flooded
CFC	Chloro fluoro carbon
CH ₄	Methane
CLIMEX	Model to predict climate change impact on species
CMS	Cell membrane stability
CO ₂	Carbon dioxide
CRI	Crop resistance index
CS	Annual cold stress

CSP	Carbon sequestration potential
CUPRAC	Cupric ion reducing antioxidant capacity
CWPs	Cell wall proteins
DAP	Diammonium phosphate
DAS	Days after sowing
DAT	Days after transplanting
DCD	Dicyandiamide
DHA	Dehydrogenase activity
DP	Drought prone
DS	Annual drought stress
DSR	Direct seeded rice
DST	Department of Science and Technology
DW	Deep water
EC	Eddy covariance
ECD	Electron capture detector
ECI	Efficiency of conversion of ingested food
EF	Emission factor
Eh	Redox potential
EI	Eco-climatic index
ET	Economic threshold
FACE	Free air carbon dioxide enrichment
FAME	Fatty acid methyl esters
FAO	Food and Agriculture Organisation
FAOE	Free air ozone enrichment
FATE	Free air temperature enrichment
FID	Flame ionization detector
FIRBS	Furrow irrigated raised-bed system
FP	Flood prone
FYM	Farmyard manure
GC	Gas chromatograph

GCM	General circulation models
Gg	Giga gram (10^9 g)
GHG	Greenhouse gases
GIS	Geographic information systems
GM	Green manure
GPS	Global positioning systems
GR	Glutathione reductase
Gt	Giga tonne (10^9 tonne)
GWP	Global warming potential
H ₂ O ₂	Hydrogen peroxide
HAT	Hydrogen atom transfer
HEI	Herbicide efficiency index
HI	Harvest index
HPLC	High performance liquid chromatography
HS	Annual heat stress
HSPs	Heat shock proteins
Hz	Hertz
IAEA	International Atomic Energy Agency, Vienna, Austria
IARI	Indian Agricultural Research Institute, New Delhi
ICAR	Indian Council of Agricultural Research, New Delhi
IEF	Isoelectric focussing
IGP	Indo-Gangetic Plains
IPCC	Inter-Governmental Panel on Climate Change
IRGA	Infra-red gas analyzer
IRRI	International Rice Research Institute, Manila
ITEX	International Tundra Experiment
IWM	Integrated Weed Management
IWM	Integrated Water Management
K	Potassium
KI	Potassium iodide

LAI	Leaf area index
LCC	Leaf colour chart
LI	Light interception
Mha	Million hactares
M	Molarity
MA	Multiple aeration
MAC	Methane Asia Campaign
MALDI TOF	Matrix-assisted laser desorption ionisation time of flight
MAPKs	Mitogen-activated protein kinases
MAS	Marker-assisted selection
MBC	Microbial biomass carbon
MBN	Microbial biomass nitrogen
MDA	Malondialdehyde
MI _w	Moisture index for week
MSI	Membrane stability index
MT	Million tonnes
N	Nitrogen
N ₂ O	Nitrous oxide
N ₂ O-N	N ₂ O calculated as amount of N
NAR	Net assimilation rate
NATCOM	National Communication to the United Nations Framework Convention on Climate Change
NATP	National Agricultural Technology Project of ICAR
NBT	Nitro-blue tetrazolium
NCU	Neem coated urea
NH ₃	Ammonia
NH ₄ ⁺ -N	NH ₄ ⁺ as amount of N
NMR	Nuclear magnatic resonance
NO ₃ ⁻ -N	NO ₃ ⁻ as amount of N
O ₃	Ozone
OTC	Open top chambers

P	Phosphorous
PAGE	Polyacrylamide gel electrophoresis
PAL	Phenylalanine ammonia-lyase
PCA	Principal component analysis
PCR	Polymerase chain reaction
PDB	Pee Dee Belemnite
PET	Potential evapotranspiration
Pg	Peta gram (10^{15} gram)
POX	Peroxidase
ppm	Parts per million
ppb	Parts per billion
ppbV	Parts per billion volume
PPO	Polyphenol oxidase
ppt	Parts per trillion
PS	Pecan shell
PVDF	Polyvinylidene fluoride
PVP	Polyvinylpyrrolidone
QTLs	Quantitative trait loci
RAPD	Identified random amplified polymorphic DNA
RCTs	Resource conserving technologies
RGR	Relative growth rate
ROS	Reactive oxygen species
RUBISCO	Ribulosebiphosphate carboxylase
SA	Single aeration
SDS PAGE	Sodium dodecylsulphate polyacrylamide gel electrophoresis
SLA	Specific leaf area
SOC	Soil organic carbon
SOD	Superoxide dismutase
SOM	Soil organic matter
SSWM	Site-specific weed management

SWD	Surface wetness duration
TCA	Trichloroacetic acid
TCD	Thermal conductivity detector
Tg	Tera gram (10^{12} g)
TGT	Temperature gradient tunnel
TIw	Temperature index for week
TPP	Trehalose-6-phosphate phosphatase
TPS	Trehalose-6-phosphate synthase
TYLCV	Tomato leaf curl virus
UDP	Uridinediphosphate
UKCIP	United Kingdom Climate Impact Programs
UNEP	United Nation Environment Programme
UNFCCC	United Nation Framework on Climate Change Convention
USDA	United States Department of Agriculture
USEPA	United States Environment Protection Agency
USG	Urea super granule
UV-radiations	Ultra violet radiations
VPD	Vapour pressure deficit
VPDB	Vienna Pee Dee Belemnite
WCE	Weed control efficiency
WCI	Weed competition index
WCI	Weed control index
WHC	Water holding capacity
WI	Weed index
WPI	Weed persistence index
WS	Annual wet stress
WSE	Weed smothering efficiency
ZT	Zero tillage

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Section I

Climate Change and Agriculture

Introduction

H Pathak

Background

For the past some decades, the gaseous composition of earth's atmosphere is undergoing a significant change, largely through increased emissions from energy, industry and agriculture sectors; widespread deforestation as well as fast changes in land use and land management practices. These anthropogenic activities are resulting in an increased emission of radiatively active gases, viz. carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), popularly known as the 'greenhouse gases' (GHGs) (Table 1). These GHGs trap the outgoing infrared radiations from the earth's surface and thus raise the temperature of the atmosphere. The global mean annual temperature at the end of the 20th century, as a result of GHG accumulation in the atmosphere, has increased by 0.4–0.7 °C above that recorded at the end of the 19th century. The past 50 years have shown an increasing trend in temperature @ 0.13 °C/decade, while the rise in temperature during the past one and half decades has been much higher

Table 1. Abundance and lifetime of greenhouse gases in the atmosphere

Parameters	CO ₂	CH ₄	N ₂ O	Chlorofluorocarbons
Average concentration 100 years ago (ppbV)	290,000	900	270	0
Current concentration (ppbV) (2007)	380,000	1,774	319	3-5
Projected concentration in the year 2030 (ppbV)	400,000-500,000	2,800-3,000	400-500	3-6
Atmospheric lifetime (year)	5-200	9-15	114	75
Global warming potential (100 years relative to CO ₂)	1	25	298	4750-10900

Source: IPCC (2007)

(Figure 1). The Inter-Governmental Panel on Climate Change has projected the temperature increase to be between 1.1 °C and 6.4 °C by the end of the 21st Century (IPCC, 2007). The global warming is expected to lead to other regional and global changes in the climate-related parameters such as rainfall, soil moisture, and sea level. Snow cover is also reported to be gradually decreasing. Therefore,

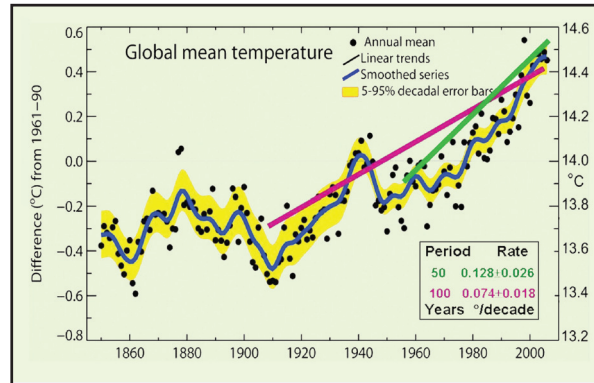


Figure 1. Trends in global temperature over the years (IPCC, 2007)

concerted efforts are required for mitigation and adaptation to reduce the vulnerability of agriculture to the adverse impacts of climate change and making it more resilient (Figure 2).

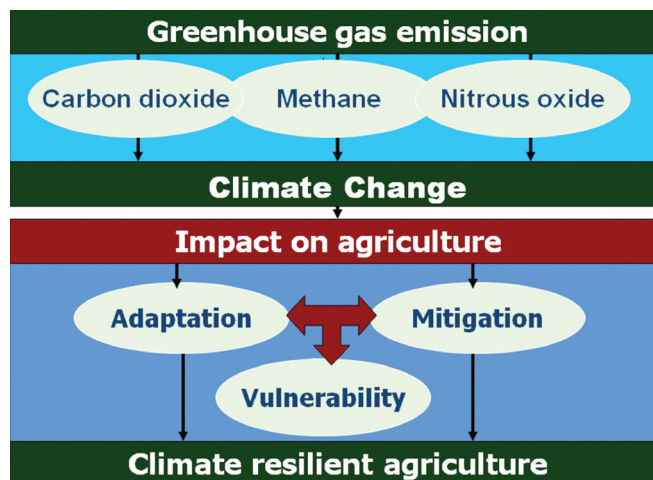


Figure 2. Framework of climate change impact, mitigation and adaptation in agriculture

The adaptive capacity of poor farmers is limited because of subsistence agriculture and low level of formal education. Therefore, simple, economically viable and culturally acceptable adaptation strategies have to be developed and implemented. Furthermore, the transfer of knowledge as well as access to social, economic, institutional, and technical resources need to be provided and integrated within the existing resources of farmers. This chapter provides an outline about the impacts of climate change on Indian agriculture and the potential strategies for their mitigation and adaptation.

Emission of Greenhouse Gases

The three major GHGs are carbon dioxide, methane and nitrous oxide, besides chlorofluorocarbons. A brief description about their sources and sinks is given below.

Carbon Dioxide

The main sources of carbon dioxide emission are decay of organic matter, forest fires, eruption of volcanoes, burning of fossil fuels, deforestation and land-use changes. Agriculture is also a contributor to CO₂ emission but is not considered a major source of this important GHG. Within agriculture, soil is the main contributor with factors such as soil texture, temperature, moisture, pH, and available C and N, influencing CO₂ emission from soil. Emission of CO₂ is more from a tilled soil than from an undisturbed soil (no till). Temperature has a marked effect on CO₂ evolution from soil by influencing root and soil respiration. It may be mentioned that plants, oceans and atmospheric reactions are the major sinks of carbon dioxide.

Methane

Methane is about 25-times more effective as a heat-trapping gas than CO₂. The main sources of methane are: wetlands, organic decay, termites, natural gas and oil extraction, biomass burning, rice cultivation, cattle and refuse landfills. The primary sources of methane from agriculture include animal digestive processes, rice cultivation and manure storage and handling. The removal in the Stratosphere and soil are the main sinks of methane.

In ruminant animals, methane is produced as a by-product of the digestion of feed in the rumen under anaerobic condition. Methane emission is related to

the composition of animal diet (grass, legume, grain and concentrates) and the proportion of different feeds (e.g., soluble residue, hemicellulose and cellulose content). Mitigation of methane emitted from livestock is approached most effectively by strategies that reduce feed input per unit of product output. Nutritional, genetic and management strategies to improve feed efficiency increase the rate of product (milk, meat) output per animal. Because most CH_4 is produced in the rumen by fermentation, practices that speed the passage of feed from the rumen can also reduce methane formation.

Methane is also formed in soil through the metabolic activities of a small but highly specific bacterial group called 'methanogens'. Their activity increases in the submerged, anaerobic conditions developed in the wetland rice fields, which limit the transport of oxygen into the soil, and the microbial activities render the water-saturated soil practically devoid of oxygen. The upland, aerobic soil does not produce methane. Water management, therefore, plays a major role in methane emission from soil. Altering water management practices, particularly mid-season aeration by short-term drainage as well as alternate wetting and drying can greatly reduce methane emission from rice cultivation. Improving organic matter management by promoting aerobic degradation through composting or incorporating into soil during off-season drain-period is another promising technique.

Nitrous Oxide

As a greenhouse gas, nitrous oxide is 298-times more effective than CO_2 . Forests, grasslands, oceans, soils, nitrogenous fertilizers, and burning of biomass and fossil fuels are the major sources of nitrous oxide, while it is removed by oxidation in the Stratosphere. Soil contributes to the largest amount of nitrous oxide emission. The major sources are soil cultivation, fertilizer and manure application, and burning of organic material and fossil fuels. From an agricultural perspective, nitrous oxide emission from soil represents a loss of soil nitrogen, reducing the nitrogen-use efficiency. Appropriate crop-management practices, which lead to increased N-use efficiency, hold the key to reduce nitrous oxide emission. Site-specific nutrient management, fertilizer placement and proper type of fertilizer supply nutrients in a better accordance with plant demands, thereby reduce nitrous oxide emission.

Impacts of Climate Change on Agriculture

Global climatic changes can affect agriculture through their direct and indirect effects on the crops, soils, livestock and pests (Table 2). An increase in atmospheric carbon dioxide level will have a fertilization effect on crops with C3 photosynthetic pathway and thus will promote their growth and productivity. The increase in temperature, depending upon the current ambient temperature, can reduce crop duration, increase crop respiration rates, alter photosynthate partitioning to economic products, affect the survival and distribution of pest populations, hasten nutrient mineralization in soils, decrease fertilizer-use efficiencies, and increase evapo-transpiration rate. Indirectly, there may be considerable effects on land

Table 2. Potential impacts of climate change on different sectors of agriculture

Sector	Impact
Crop	• Increase in ambient CO₂ concentration is beneficial since it leads to increased photosynthesis in several crops, especially those with C3 mechanism of photosynthesis such as wheat and rice, and decreased evaporative losses. Despite this, yields of major cereals crops, especially wheat are likely to be reduced due to decrease in grain filling duration, increased respiration, and / or reduction in rainfall/irrigation supplies. • Increase in extreme weather events such as floods, droughts, cyclones and heat waves will adversely affect agricultural productivity. • Reduction in yields in the rainfed areas due to changes in rainfall pattern during monsoon season and increased crop water demand. • Incidence of cold waves and frost events may decrease in future due to global warming and it would lead to a decreased probability of yield loss associated with frost damage in northern India in crops such as mustard and vegetables. • Quality of fruits, vegetables, tea, coffee, aromatic, and medicinal plants may be affected. • Incidence of pest and diseases of crops to be altered because of more enhanced pathogen and vector development, rapid pathogen transmission and increased host susceptibility. • Agricultural biodiversity is also threatened due to the decrease in rainfall and increase in temperature, sea level rise, and increased frequency and severity of droughts, cyclones and floods.
Water	• Demand for irrigation water would increase with rise in temperature and evapo-transpiration rate. It may result in lowering of groundwater table at some places.

contd...

Table 2 contd....

Sector	Impact
Soil	- The melting of glaciers in the Himalayas will increase water availability in the Ganges, Bhramaputra and their tributaries in the short-run, but in the long-run, the availability of water will decrease considerably. - A significant increase in runoff is projected in the wet season that, however, may not be very beneficial unless storage infrastructure is vastly expanded. This additional water in the wet season, on the other hand, may lead to increase in frequency and duration of floods. - The water balance in different parts of India will be disturbed and the quality of groundwater along the coastal track will be affected more due to intrusion of sea waters.
	- Organic matter content, which is already quite low in Indian soils, would become still lower. Quality of soil organic matter may be affected. - The residues of crops under the elevated CO₂ concentrations will have higher C:N ratio, and this may reduce their rate of decomposition and nutrient supply. - Rise in soil temperature will increase N mineralization, but its availability may decrease due to increased gaseous losses through processes such as volatilization and denitrification. - There may be a change in rainfall volume and frequency, and wind may alter the severity, frequency and extent of soil erosion. - Rise in sea level may lead to salt-water ingress in the coastal lands, turning them less suitable for conventional agriculture.
	Livestock
	- Climate change will affect fodder production and nutritional security of livestock. Increased temperature would enhance lignification of plant tissues, reducing the digestibility. Increased water scarcity would also decrease production of feed and fodder. - Major impacts on vector-borne diseases will be through expansion of vector populations in the cooler areas. Changes in rainfall pattern may also influence expansion of vectors during wetter years, leading to large outbreaks of diseases. - Global warming would increase water, shelter, and energy requirement of livestock for meeting the projected milk demands. - Climate change is likely to aggravate the heat stress in dairy animals, adversely affecting their reproductive performance.
	Fishery

Source: Aggarwal *et al.* (2009a)

use due to snow melt, availability of irrigation water, frequency and intensity of inter- and intra-seasonal droughts and floods, soil organic matter transformations, soil erosion, changes in pest profiles, decline in arable areas due to submergence of coastal lands, and availability of energy. Equally important determinants of food supply are socio-economic environment, including government policies, capital availability, prices and returns, infrastructure, land reforms, and inter- and intra-national trade that might be affected by the climatic change.

Reduction in Crop Yield

Rise in the mean temperature above a threshold level will cause a reduction in agricultural yields. A change in the minimum temperature is more crucial than a change in the maximum temperature. Grain yield of rice, for example, declined by 10% for each 1 °C increase in the growing season minimum temperature above 32 °C (Pathak *et al.*, 2003). The climate change impact on the productivity of rice in Punjab (India) has shown that with all other climatic variables remaining constant, temperature increases of 1 °C, 2 °C and 3 °C, would reduce the grain yield of rice by 5.4%, 7.4% and 25.1%, respectively (Aggarwal *et al.*, 2009b).

Shortage of Water

The increased temperature would result in more water shortages and the demand for irrigation water would rise. Increase in air temperature will lead to more potential evapotranspiration in the areas south of 40° N. Likewise, water shortage due to climate change would result in about 20% net decline in the rice yields in India.

Irregularities in Onset of Monsoon, Drought, Flood and Cyclone

Indian agriculture is highly dependent on the onset, retreat and magnitude of monsoon precipitation, particularly in the rainfed areas of east, north-east and south India. Climate modelers and IPCC documents have projected possibilities of increasing variability in Asian Monsoon circulation in a warmer world. Despite expansion of area under irrigation, droughts, caused by inadequate and uneven distribution of rainfall, continue to be the most important climatic aberrations, which influence the agricultural production in India. The severity of a drought will be intensified in a warmer world. Intense and frequent floodings due to climate change would be a major problem in the Indian subcontinent.

Rise in Sea Level

In South, South East and East Asia about 10% of the regional rice production, which is enough to feed 200 million people, is from the areas that are susceptible to 1 m rise in the sea level. Direct loss of land combined with less favourable hydraulic conditions may reduce rice yields by 4% if no adaptation measures are taken, endangering the food security of at least of 75 million people. Saltwater intrusion and soil salinization are other concerns for agricultural productivity.

Decline in Soil Fertility

Soil temperature affects the rates of organic matter decomposition and release of nutrients. At high temperatures, though nutrient availability will increase in the short-term, in the long-run organic matter content will diminish, resulting in a decline in soil fertility.

Loss of Biodiversity

Species of animals and plants are estimated to disappear at a rate which would be about 100-times faster than the historical record, largely as a result of human activities. A detailed assessment of the 394 species of primates from South America to Indonesia has indicated that 29% are in danger of disappearing due to hunting, habitat loss and climate change.

Pests, Weeds and Diseases

As temperature increases, the insect-pests will become more abundant through a number of inter-related processes, including range extensions and phenological changes, as well as increased rates of population development, growth, migration and over-wintering. The climate change is likely to alter the balance between insect pests, their natural enemies and their hosts. The rise in temperature will favour insect development and winter survival. Rising atmospheric carbon dioxide concentrations may lead to a decline in food quality for plant-feeding insects, as a result of reduced foliar nitrogen levels. The epidemiology of plant diseases will be altered. The prediction of disease outbreaks will be more difficult in periods of rapidly changing climate and unstable weather. Environmental instability and increased incidence of extreme weather may reduce the effectiveness of pesticides on targeted pests or result in more injury to non-target organisms.

Mitigation Strategies to Climate Change

The strategies for mitigating methane emission from rice cultivation could be alteration in water management, particularly promoting mid-season aeration by short-term drainage; improving organic matter management by promoting aerobic degradation through composting or incorporating it into soil during off-season drained period; use of rice cultivars with few unproductive tillers, high root oxidative activity and high harvest index; and application of fermented manures like biogas slurry in place of unfermented farmyard manure (Pathak and Wassmann, 2007). Methane emission from ruminants can be reduced by altering the feed composition, either to reduce the percentage which is converted into methane or to improve the milk and meat yield.

The most efficient management practice to reduce nitrous oxide emission is site-specific, efficient nutrient management (Pathak, 2010). The emission could also be reduced by nitrification inhibitors such as nitrapyrin and dicyandiamide (DCD). There are some plant-derived organics such as neem oil, neem cake and karanja seed extract which can also act as nitrification inhibitors.

Mitigation of CO₂ emission from agriculture can be achieved by increasing carbon sequestration in soil through manipulation of soil moisture and temperature, setting aside surplus agricultural land, and restoration of soil carbon on degraded lands. Soil management practices such as reduced tillage, manuring, residue incorporation, improving soil biodiversity, micro aggregation, and mulching can play important roles in sequestering carbon in soil. Some technologies such as intermittent drying, site-specific N management, etc. can be easily adopted by the farmers without additional investment, whereas other technologies need economic incentives and policy support (Wassmann and Pathak, 2007).

Adaptation Strategies to Climate Change

To deal with the impact of climate change, the potential adaptation strategies are: developing cultivars tolerant to heat and salinity stress and resistant to flood and drought, modifying crop management practices, improving water management, adopting new farm techniques such as resource conserving technologies (RCTs), crop diversification, improving pest management, better weather forecasting and crop insurance and harnessing the indigenous technical knowledge of farmers. Some of these strategies are discussed below.

Developing Climate-ready Crops

Development of new crop varieties with higher yield potential and resistance to multiple stresses (drought, flood, salinity) will be the key to maintain yield stability. Improvement in germplasm of important crops for heat-stress tolerance should be one of the targets of breeding programme. Similarly, it is essential to develop tolerance to multiple abiotic stresses as they occur in nature. The abiotic stress tolerance mechanisms are quantitative traits in plants. Germplasm with greater oxidative stress tolerance may be exploited as oxidative stress tolerance is one example where plant's defence mechanism targets several abiotic stresses. Similar to the research efforts on conversion of rice from C3 to C4 crop, steps should be taken for improvement in radiation-use efficiency of other crops as well.

Improvement in water-use and nitrogen-use efficiencies is being attempted since long. These efforts assume more relevance in the climate change scenarios as water resources for agriculture are likely to dwindle in future. Nitrogen-use efficiency may be reduced under the climate change scenarios because of high temperatures and heavy precipitation events causing volatilization and leaching losses. Apart from this, for exploiting the beneficial effects of elevated CO₂ concentrations, crop demand for nitrogen is likely to increase. Thus, it is important to improve the root efficiency for mining the water and absorption of nutrients. Exploitation of genetic engineering for 'gene pyramiding' has become essential to pool all the desirable traits in one plant to get the 'ideal plant type' which may also be 'adverse climate-tolerant' genotype.

Farmers need to be provided with cultivars with a broad genetic base. Their adaptation process could be strengthened with availability of new varieties having tolerance to drought, heat and salinity and thus, minimize the risks of climatic aberrations. Similarly, development of varieties is required to offset the emerging problems of shortening of growing season and other vagaries of production environment. Farmers could better stabilize their production system with basket of technological options.

Crop Diversification

Diversification of crop and livestock varieties, including replacement of plant types, cultivars, hybrids, and animal breeds with new varieties intended for higher drought or heat tolerance, are being advocated as having the potential to increase

productivity in the face of temperature and moisture stresses. Diversity in the seed genetic structure and composition has been recognized as an effective defence against disease and pest outbreak and climatic hazards. Moreover, demand for high-value food commodities, such as fruits, vegetables, dairy, meat, eggs and fish is increasing because of growing income and urbanization. This is reducing the demand for traditional rice and wheat. Diversification from rice-wheat towards high-value commodities will increase income and result in reduced water and fertilizer use. However, there is a need to quantify the impacts of crop diversification on income, employment, soil health, water use and greenhouse gas emissions. A significant limitation of diversification is that it is costly in terms of the income opportunities that farmers forego, i.e., switching of crop can be expensive, making crop diversification typically less profitable than specialization. Moreover, traditions can often be difficult to overcome and will dictate local practices.

Changes in Land-use Management Practices

Changing land-use practices such as the location of crop and livestock production, rotating or shifting production between crops and livestock, shifting production away from marginal areas, altering the intensity of fertilizer and pesticide application as well as capital and labour inputs can help reduce risks from climate change in farm production. Adjusting the cropping sequence, including changing the timing of sowing, planting, spraying, and harvesting, to take advantage of the changing duration of growing seasons and associated heat and moisture levels is another option. Altering the time at which fields are sowed or planted can also help farmers regulate the length of the growing season to better suit the changed environment. Farmer adaptation can also involve changing the timing of irrigation or use of other inputs such as fertilizers.

Adjusting Cropping Season

Adjustment of planting dates to minimize the effect of temperature increase-induced spikelet sterility can be used to reduce yield instability, by avoiding having the flowering period to coincide with the hottest period. Adaptation measures to reduce the negative effects of increased climatic variability as normally experienced in arid and semi-arid tropics may include changing of the cropping calendar to take advantage of the wet period and to avoid extreme weather events (e.g., typhoons and storms) during the growing season. Cropping systems may have

to be changed to include growing of suitable cultivars (to counteract compression of crop development), increasing crop intensities (i.e., the number of successive crop produced per unit area per year) or planting different types of crops. Farmers will have to adapt to changing hydrological regimes by changing crops.

Efficient Use of Resources

The resource-conserving technologies (RCTs) encompass practices that enhance resource- or input-use efficiency and provide immediate, identifiable and demonstrable economic benefits such as reduction in production costs; savings in water, fuel and labour requirements; and timely establishment of crops, resulting in improved yields. Yields of wheat in heat- and water-stressed environments can be raised significantly by adopting RCTs, which minimize unfavourable environmental impacts, especially in small and medium-scale farms. Resource conserving practices like zero-tillage (ZT) can allow farmers to sow wheat sooner after rice harvest, so the crop heads and fills the grain before the onset of pre-monsoon hot weather. As the average temperatures in the region rise, early sowing will become even more important for wheat. Field results have shown that the RCTs are increasingly being adopted by farmers in the rice-wheat belt of the Indo-Gangetic Plains because of several advantages of labour saving, water saving, and early planting of wheat. The RCTs in rice-wheat system also have pronounced effects on mitigation of greenhouse gas emission and adaptation to climate change (Pathak *et al.* 2009). These approaches of crop management should be coupled with the measures of crop improvement for wider adaptation to climate change.

Soil and water management is highly critical for adaptation to climate change. With higher temperatures and changing precipitation patterns, water will further become a scarce resource. Serious attempts towards water conservation, water harvesting improvement in irrigation accessibility, and water-use efficiency will become essential for crop production and livelihood management. Farmers have to be trained and motivated for adopting on-farm water conservation techniques, micro-irrigation systems for better water-use efficiency, selection of appropriate crops, etc. Principles of increasing water infiltration with improvement in soil aggregation, decreasing runoff with use of contours, ridges, vegetative hedges, etc. and reducing soil evaporation with use of crop residues mulch could be employed for better management of soil-water.

Relocation of Crops in Alternative Areas

Climate change in terms of increased temperature, CO₂ level, droughts and floods would affect production of crops. But, the impact will be different across crops and regions. There is a need to identify the crops and regions that are more sensitive to climate changes/variability and relocate them in more suitable areas. For example, it is apprehended that increased temperature would affect the quality of crops, particularly important aromatic crops such as basmati rice and tea. Alternative areas that would become suitable for such crops from quality point of view need to be identified and assessed for their suitability.

Harnessing Indigenous Technical Knowledge of Farmers

Farmers in South Asia, often poor and marginal, are experimenting with the climatic variability for centuries. There is a wealth of knowledge on the range of measures that can help in developing technologies to overcome climate vulnerabilities. There is a need to harness that knowledge and fine-tune them to suit the modern needs. Traditional ecological knowledge of people developed and carried which have stood the test of time could provide insights and viable options for adaptive measures. Anthropological and sociological studies have highlighted the importance of community based resource management and social learning to enhance their capacity to adapt to the impacts of future climate change. Tribal and hill knowledge systems are pregnant with potential indigenous practices used for absorption and conservation of rainwater, nutrient and weed management, crop production and plant protection. Their belief systems have effectively helped in weather forecasting and risk adjustment in crop cultivation. During the course of their habitation, the indigenous people of Himalayan terrain region through experience, experimentation and accumulated knowledge, have devised ways of reducing their vulnerability to natural hazards. Studies have shown that their understanding was fairly evolved in the matters of earthquake, landslide and drought and they have devised efficient ways of mitigating the effect of natural or climatic changes.

Improved Pest Management

Changes in temperature and variability in rainfall would affect incidence of pests and disease and virulence of major crops. It is because climate change will potentially affect the pest/weed-host relationship by affecting the pest/

weed population, the host population and the pest/weed-host interactions. Some of the potential adaptation strategies could be: (i) developing cultivars resistance to pests and diseases; (ii) adoption of integrated pest management with more emphasis on biological control and changes in cultural practices, (iii) pest forecasting using recent tools such as simulation modelling, and (iv) developing alternative production techniques and crops, as well as locations, that are resistant to infestations and other risks. Management of pests and diseases with use of resistant varieties and breeds; alternative natural pesticides; bacterial and viral pesticides; pheromones for disrupting pest reproduction, etc. could be adopted for sustainability of agricultural production process. Bio-agents have a crucial role in pest management, hence practices to promote natural enemies like release of predators and parasites; improving the habitat for natural enemies; facilitating beetle banks and flowering strips; crop rotation and multiple cropping should be integrated in pest management practices. Reduction in use of pesticides will also help in reducing carbon emissions.

Better Weather Forecasting and Crop Insurance Schemes

Weather forecasting and early warning systems will be very useful in minimizing risks of climatic adversaries. Information and communication technologies (ICT) could greatly help the researchers and administrators in developing contingency plans. Effective crop insurance schemes should be evolved to help the farmers in reducing the risk of crop failure due to these events. Both formal and informal, as well as private and public, insurance programs need to be put in place to help reduce income losses as a result of climate-related impacts. However, information is needed to frame out policies that encourage effective insurance opportunities.

Micro-finance has been a success among rural poor, including women. Low-cost access to financial services could be a boon for vulnerable farmers. Growing network of mobile telephony could further speed up SMS-based banking services and help the farmers in having better integration with financial institutions. However, compared to micro-finance, micro-insurance innovations and availability is limited. There is a need to develop sustainable insurance system, while the rural poor are to be educated about availing such opportunities.

Conclusions

Climatic changes and increasing climatic variability are likely to aggravate the problems of future food security by exerting pressure on agriculture. However, there are lot of uncertainties about the assessment of impact, adaptation and mitigation of climate change in agriculture. It is mainly because the methodology followed for such assessments is not standardized and sometimes is inaccurate and imprecise. Researchers follow different methodologies and arrive at contrasting results making it still more difficult to reach a logical conclusion and develop policy actions. There is a need to develop and apply a standard methodology across the board for various studies related to climate change and agriculture. The different chapters of this book present the recent, internationally accepted, and standard methodologies for studying the impacts of climate change on agriculture, measuring and developing inventories of greenhouse gas emissions, analyzing the vulnerabilities and application of adaptation and mitigation options.

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Section II

Measurement of Greenhouse Gas Emission from Agriculture

Greenhouse Gas Emission from Agriculture

H Pathak, A Bhatia and N Jain

Introduction

The sunlight enters a greenhouse through the transparent glass or plastic and heats the plants but the heat emitted by the plants in the form of infrared radiations cannot pass through the glass or plastic roof and walls of the greenhouse. As a result, temperature inside the greenhouse rises. The phenomenon is known as 'greenhouse effect'. In a similar manner, the earth's atmosphere, which acts like the glass or plastic roof and walls of a greenhouse, allows most of incoming sunlight to pass through and heat the surface. But the heat radiated by the heated surface cannot pass freely into the space because of the presence of a number of gases such as carbon dioxide, methane, ozone, nitrous oxide and water vapour in the atmosphere. Consequently, the average temperature of earth's atmosphere is increasing — a phenomenon which is commonly known as global warming. It has been found that carbon dioxide contributes 60%, methane 15% and nitrous oxide 5% to the global warming (IPCC, 2007). Also, as a heat-trapping gas, methane is 25-times and nitrous oxide is 298-times more effective than carbon dioxide (Table 1). Wetlands, organic matter decay, cattle and refuse landfills, termites and natural gas and oil extraction are the main sources of methane, whereas escape into the stratosphere and adsorption by soil are the main sinks. The primary sources of methane emission in agriculture include rice cultivation, biomass burning, animal digestive processes and manure storage and handling. Forests, grasslands, oceans, soils, nitrogenous fertilizers, burning of biomass and fossil fuels are the sources of nitrous oxide, while it is removed by oxidation in the stratosphere. Soil with a contribution of about 65% is the major contributor to the total nitrous oxide emission. The main processes that cause emission of nitrous oxide are soil cultivation, fertilizer and manure application, and burning of organic materials and fossil fuels. The main sources of carbon dioxide are decay of organic matter, forest fires, eruption of volcanoes, burning of fossil fuels, deforestation and land-use change, whereas plants, oceans and atmospheric reactions are the major sinks. Though agricultural soil is a

Table 1. Atmospheric concentration, lifetime and global warming potential (GWP) of major greenhouse gases

Greenhouse gas	Atmospheric concentration	Lifetime (years)	GWP (100 years)
Carbon dioxide	387 ppm	Variable	1
Methane	1780 ppb	12	25
Nitrous oxide	319 ppb	114	298
CFC 11	250 ppt	45	4600
CFC 12	533 ppt	100	10600
HCFC 22	132 ppt	11.9	1700
HFC 23	12 ppt	260	12000

Source: IPCC (2007)

small contributor of carbon dioxide, factors such as soil texture, temperature, moisture, pH, available C and N contents influence CO₂ emission from soil.

Measurement of Methane and Nitrous Oxide Emission

Methods used for the measurement of greenhouse gases (GHGs) vary with respect to gas to be measured, spatial coverage, temporal resolution, cost, precision and accuracy of the method. The measured values, however, can only be interpreted accurately if factors related to soil, plant and climate, which determine the production, consumption and emission of the greenhouse gases, are taken into account. Among these, soil texture, pH, organic matter content, moisture content, nitrate and ammonium content, redox potential, plant cover, and climatic factors such as air temperature, incoming radiation, relative humidity and precipitation are important. Soil physical factors such as bulk density, porosity and pore size distribution are also important in determining the storage and movement of gases in the soil.

Two methods generally used to measure methane and nitrous oxide emissions from soils are:

- (i) Soil Chamber Method, and
- (ii) Micrometeorology

- *Soil Chamber Method* — In this method, gas emissions from soil are estimated by measuring the short-term buildup of the gas in a sealed enclosure placed over the soil surface. This restricts the volume of air exchange across the covered surface. Any net emission or uptake from soil can be measured as a change in the concentration of the gas. The soil closed-chamber method is the widely used and is relatively less expensive method to estimate emissions of GHGs from soil.
- *Micrometeorology* — In this method, vertical concentration gradients of the gas measured using eddies correlation. It is useful for evaluating regional model simulations (scaling from site to region). However, requirement of expensive equipments and cumbersome sampling and measurement procedures restrict its use for estimation of methane and nitrous oxide. The details of this method are described in Chapter 3.

Closed Chamber Method

Using closed chambers the gas flux from a soil can be determined by collecting gas samples periodically from the chambers and measuring the change in concentration of a gas with time during the period of linear concentration change (Hutchison and Mosier 1981). Chambers can be made from a material like rigid plastic, metal or acrylic sheet. For collecting gas samples from crop fields, generally, chambers with dimensions of 50 cm × 30 cm × 100 cm (Figure 1) made of 6-mm

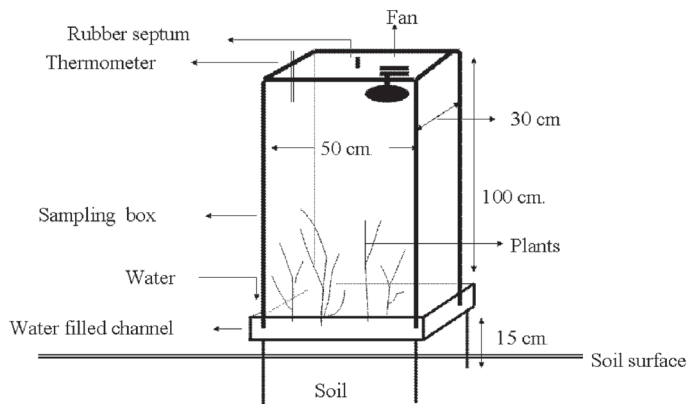


Figure 1. Closed-chamber used for collection of methane and nitrous oxide samples from a field

acrylic sheets are used. Aluminum channels, used with each chamber, are inserted 10-cm into the soil and the channels are filled with water to make the system air-tight. A battery-operated fan is fixed inside the chamber to homogenize the inside air. A thermometer is also inserted to record the inside temperature.

To measure a gas flux, the chamber is fixed on the top of the pre-inserted aluminum channels. The change in concentration of methane or nitrous oxide with time is determined by taking gas samples from the chamber headspace with the help of a syringe. The plastic or preferably greased glass medical syringes of 20-50 mL capacity and fitted with a 2-way or 3-way stop cock are generally used. Gas samples are collected from the headspace immediately after sealing and at equal time intervals thereafter over a period not exceeding 2 hours. Gas samples are drawn with the help of a hypodermic needle (24 gauges). After drawing the sample, syringes are made air-tight with a three-way stopcock. A minimum of three measurements should be made to check linearity in increase in concentration of a gas. A deviation from a straight line indicates either an inadequately sealed chamber or a decrease in the gas concentration gradient between the zone of production in the soil and the chamber atmosphere changes the gas diffusion rate with time. The gas samples are analyzed using a gas chromatograph (GC). The chamber cover should be removed after the final sample to minimize the disturbance to environmental conditions within the enclosure formed by the chamber walls. Samples of four replications of each treatment are taken from the fields and the average is taken as the representative value for the treatment. Head space volume and temperature inside the chamber are also recorded, which are used to calculate the flux of gas.

To transport gas samples over long distances to the analytical laboratory, evacuated vials fitted with rubber/silicon septa (e.g. vacutainers/exetainers) may be used. The septa of the vials should be cleaned with a detergent and the vials be evacuated using a vacuum pump before use. An alternative method is the use of glass serum bottles fitted with butyl rubber stoppers. The vials are taken to the sampling site, and filled with the gas sample with a syringe. By injecting sufficient volume of gas sample to achieve over-pressure, e.g. 10 mL into a 9-mL vial, contamination problems can be prevented.

The methodology has been described step-wise in the following sections.

Collection of Gas Samples

- Gas sample is collected using closed-chamber technique (Figure 1).
- Chambers of 50 cm × 30 cm × 100 cm size (according to experiment) made of 5 to 6-mm acrylic sheets are required for sampling.
- An aluminum channel is placed in the field and is used with each acrylic chamber.
- The aluminum channels should be inserted 10 cm inside the soil and the channels are filled with water to make the system air-tight.
- One 3-way stopcock (Eastern Medikit Ltd. India) is fitted at the top of chamber to collect gas samples.
- The chamber should be thoroughly flushed several times with a 50-mL syringe to homogenize the inside air thoroughly.
- Gas samples are to be drawn with the help of a 20-50 mL syringe using a hypodermic needle (24 gauges).
- After drawing samples, the chamber should be made air tight with the help of a stop cock.
- Head space volume inside the box should be recorded, which will be used to calculate flux of gas (nitrous oxide or methane).
- Gas samples are collected at 0 hour, ½ hour and 1 hour after the chamber has been placed over the aluminium channel.

Estimation of Greenhouse Gases

Methane

In gas samples, the concentration of methane is estimated using a Gas Chromatograph fitted with a flame ionization detector (FID). The FID detects the substances that produce ions when heated in H₂-air flame. The detector, however, is insensitive to permanent gases, water and inorganic ions, which do not ionize at 2100 °C. The sample along with the carrier gas (eluent) enters the hydrogen jet via a millipore filter. The sample components get ionized to form ions and free electrons on entering the flame at the tip of the jet. The electrons so produced are drawn towards a collector. Due to this movement of electrons, there is a flow of current. The flow of current across an external resistor, sensed as voltage drop, is amplified and displayed on the recorder. The entire assembly is housed in an oven to prevent condensation of water vapour formed as a result of combustion.

Gas samples containing methane are introduced into the gas chromatograph through a sampling valve with the help of a syringe fitted with a two-way nylon stopcock. A gas sample loop of 1 or 2 cm³ is fitted to the sample valve. Although, it is possible to inject the sample manually, use of a sample loop should be preferred. The configuration of the valve may be designed as per the needs of user. Methane analysis can be accomplished by various modifications of GC settings and column materials. Each individual setting will have to be optimized empirically in order to achieve a satisfactory separation and detection.

Methane can be separated from other gaseous components on a Porapak N or Porapak Q column (3-m-long stainless steel or nickel with 3.175-mm outside diameter) maintained at 50 °C having a carrier gas flow (helium, nitrogen or argon) of 20-30 cm³ min⁻¹. An alternative is the use of a molecular sieve (13 × 60-80 mesh size) as a column material and synthetic air as carrier gas. Methane is detected with the help of a FID maintained at 250 °C. Column temperature is maintained at 70 °C. H₂ with a flow rate of 30-40 mL min⁻¹ is used for FID. The sampling valve can be accentuated manually or time-controlled pneumatically or electronically using a computer or GC-contained microprocessor. A GC-computer interface is used to plot and measure the peak area. The methane standards (1 ppm, 5 ppm and 10 ppm) are used as a primary standard.

Calculation of Methane Flux

$$\begin{aligned}
 \text{Cross-sectional area of the chamber (m}^2\text{)} &= A \\
 \text{Headspace (m)} &= H \\
 \text{Volume of headspace (L)} &= 1000 \times AH \\
 \text{CH}_4 \text{ concentration at 0 time (}\mu\text{L L}^{-1}\text{)} &= C_o \\
 \text{CH}_4 \text{ concentration after time } t \text{ (}\mu\text{L L}^{-1}\text{)} &= C_t \\
 \text{Change in concentration in time } t \text{ (}\mu\text{L L}^{-1}\text{)} &= (C_t - C_o) \\
 \text{Volume of CH}_4 \text{ evolved in time } t \text{ (}\mu\text{L)} &= (C_t - C_o) \times 1000 AH \\
 \text{When } t \text{ is in hours, then flux (mL m}^{-2} \text{ h}^{-1}\text{)} &= [(C_t - C_o) \times AH] / (A \times t) \\
 \text{Now 22.4 mL of CH}_4 \text{ is 16 mg at STP} \\
 \text{Hence, Flux} &= [(C_t - C_o) / t] \times H \times 16 / 22.4 \times 10000 \times 24 \text{ mg ha}^{-1} \text{ d}^{-1}
 \end{aligned}$$

Nitrous Oxide

In gas samples, the concentration of nitrous oxide is estimated with the help of a Gas Chromatograph fitted with an electron capture detector (ECD) and

6' × 1/8" stainless steel column (Porapak N). The ECD is used for the detection of those substances which have affinity for electrons. The detector consists of two electrodes, one of which is treated with radioactive ^{63}Ni , which emits beta rays. These high-energy electrons bombard the carrier gas (N_2 or argon mixture) to produce a large number of low-energy (or thermal) secondary electrons. The other positively polarized electrode collects these electrons. This steady state current is reduced when an electrophilic sample component passing through the gap between the two electrodes captures some of these electrons, thus providing an electrical reproduction of the GC peak. This detector can also contain besides ^{63}Ni some other radioactive elements like tritium or scandium. Although the sensitivity of ^{63}Ni is lower, it remains constant for a longer duration and surpasses the sensitivity of a tritium cell of the same age.

The temperatures of column and detector are kept at 50 °C, and 320 °C, respectively. The flow rates of carrier gas back flush and detector purge gases (95% argon + 5% methane or N_2) are kept as 14-18 $\text{cm}^3 \text{min}^{-1}$. Gas samples are introduced into a gas sampling loop (size depends upon the sensitivity of the ECD used) through an inlet system. Both CO_2 and water vapours are removed from the gas samples. The two absorbent traps are prepared by packing 10-mm millipore syringe filter holders with Ascarite and MgClO_4 .

A GC-computer interface is used to plot and measure the peak area. The N_2O standard (500 ppbV) is used as a primary standard.

Calculation of N_2O Flux

Cross-sectional area of the chamber (m^2)	=	A
Headspace (m)	=	H
Volume of headspace (L)	=	1000 × AH
CH_4 concentration at 0 time ($\mu\text{L L}^{-1}$)	=	C_o
CH_4 concentration after time t ($\mu\text{L L}^{-1}$)	=	C_t
Change in concentration in time t ($\mu\text{L L}^{-1}$)	=	$(C_t - C_o)$
Volume of CH_4 evolved in time t (μL)	=	$(C_t - C_o) \times 1000 \text{ AH}$
When t is in hours, then flux ($\text{mL m}^{-2} \text{h}^{-1}$)	=	$[(C_t - C_o) \times \text{AH}] / (A \times t)$

Now, 22.4 mL of N_2O is 44 mg at STP

Hence, Flux = $[(C_t - C_o) / t] \times H \times 44 / 22.4 \times 10000 \times 24 \text{ mg ha}^{-1} \text{d}^{-1}$

Advantages of Closed Chamber Method

- Very small gas fluxes can be measured
- No additional equipment for electric supply is needed
- There is a little disturbance in the site due to the short-time for which the cover is placed for each gas flux estimate
- The chambers are simple and relatively less expensive with a variety of readily available materials, which are inert to the gas of interest
- Chambers can be installed and removed easily, facilitating measurement
- Especially useful for addressing research objectives served by discrete observation in space and time
- In combination with appropriate sample allocations, it is adaptable to a wide variety of studies on the local to global spatial scales
- It is suited to *in situ* as well as laboratory-based studies addressing physical, chemical and biological controls of surface-atmosphere trace gas exchange
- It is good for short deployment period and low exchange rate

Precautions

While using the closed chamber technique for GHG flux measurement, following precautions should be taken:

- Chamber height should be more than 30 cm
- The chamber headspace N_2O concentration at zero hour should be measured accurately. For this, the first air sample inside the chamber should be taken immediately after the chamber placement on the channel/collar in case of cylindrical chambers.
- Air samples should be taken in as short a time as possible to observe a measureable increase in headspace gas concentration. Longer chamber deployment durations may result in negative impacts.

Limitations of the Method and their Addressal

In spite of being simple and popular, the closed chamber method has following limitations:

- Concentrations of gas in the chamber may build up to the levels at which the normal emission rate gets inhibited. However, the problem can be minimized by using shorter collection periods.
- Closed chambers alter the atmospheric pressure fluctuations, which are found at the soil surface due to the natural turbulence of air movement. Thus, a closed chamber may underestimate the flux of a gas.
- This problem may be overcome by an appropriately designed vent, which allows pressure equilibration in and outside the chamber.
- Variations in temperature may occur in soil and inside the chamber. However, insulating the chamber and covering it with a reflective material can reduce the temperature difference.

For conducting round-the-clock emission measurements and overcoming some of the above limitations, automatic sampling devices are very useful. In these devices, the air samples from the inner space of the gas collecting chamber are replaced by a gas flow system providing a periodic sample transfer to the gas chromatograph. However, the automatic sampling devices are costly and their use is confined to those locations where the laboratory is in the vicinity of the experimental field. The automatic sampling system may be used extensively in the long-term field measurements of GHGs at different experimental stations. The basic components of an automatic sampling system are: Gas collecting chambers (boxes) equipped with removable covers, gas flow system (tubing, pump), sampling unit, analytical unit (GC and integrator), time control and data acquisition systems. It allows continuous round-the-clock and simultaneous measurements at several locations for the entire growing season, as is necessary for obtaining data on diurnal and seasonal variations in emission rates under the field conditions.

Practical Considerations to Reduce the Uncertainties

- **Number of chambers:** Due to high spatial variability, the more the number of chambers, the less is the uncertainty.
- **Sampling frequency:** Due to high temporal variability, the more often we sample, the less is the uncertainty.
- **Chamber size:** Due to high microscale variability, bigger is usually better.
- **Chamber deployment time:** Longer period of sampling results in better precision; too long, however, may yield sampling artefacts.

Measurement of Carbon Dioxide Emission from Soil

For the quantitative analysis of CO_2 emission from soil, four methods are used: (1) Alkali trap method, (2) Soil respirator method, (3) Infrared gas analyzer method, and (4) Closed-chamber method.

(1) Alkali Trap Method

In this method, CO_2 is trapped in aqueous solution of alkali (usually KOH or NaOH), and is precipitated as BaCO_3 by adding BaCl_2 in excess. The precipitate is collected, washed, dried and weighed. The volumetric estimation of CO_2 trapped in aqueous alkali is a popular method because of its simplicity and high degree of sensitivity. For measurement of CO_2 evolution, alkali solution of a known concentration is placed in an open jar on the soil surface, and the area to be measured is covered with a metal cylinder closed at the upper end. The CO_2 evolved from the soil surface is trapped in the cylinder and remains confined there until it is absorbed by the alkali. After a certain period of time, the alkali is removed and its unreacted portion is determined by titration. By subtraction, the amount of CO_2 that combined with the alkali is determined.

A CO_2 trap is prepared by pipetting 20 mL of 1N NaOH into a glass jar which is placed on a tripod stand. Immediately, a metal cylinder is placed over the alkali trap, and pressed at the edges by about 2 cm into the surface of the soil. The cylinder should be shielded from the direct sunlight by covering with either a sheet of wood or a piece of aluminum foil. After exposure of the alkali for 2-4 hours, the jar is removed, covered with lids (airtight seal), and brought to the laboratory for analysis. Controls for this experiment consist of jars of alkali that are incubated in the field in completely sealed metal cylinders by closing the open ends with tightly fitting lids. The airtight seal between lid and cylinder can be obtained by smearing the edge with silicon grease. The alkali solutions from the controls and those exposed to the soil air are titrated to determine the quantity of alkali that has not reacted with CO_2 . For this purpose, excess BaCl_2 is added to the NaOH solution to precipitate the carbonate as insoluble BaCO_3 . A few drops of phenolphthalein are added as indicator, and the solution is titrated with aq. HCl directly in the jar. The acid should be added slowly to avoid contact with and possible dissolution of the precipitated BaCO_3 . The volume of acid needed to neutralize the alkali is noted. The amount of CO_2 evolved from the soil during exposure to alkali may be calculated using formula (1):

$$\text{Milligrams of C or CO}_2 = (B - V) NE \quad \dots(1)$$

where, B = volume (mL) of acid needed to titrate NaOH in the jar from the control cylinder, V = volume (mL) of acid needed to titrate the NaOH in the jar exposed to the soil atmosphere, N = normality of the acid, and E = equivalent weight of acid. To express the data in terms of carbon, $E = 6$; to express it as CO_2 , $E = 22$. Once the milligrams of CO_2 -C or CO_2 have been determined, the data are conveniently expressed as $\text{mg of CO}_2 \text{ m}^{-2} \text{ h}^{-1}$.

(2) Soil Respirometer Method

The soil respiration, i.e., flux of CO_2 per unit area per unit time, is measured by placing a closed-chamber on the soil and measuring the rate of increase in the CO_2 concentration inside the chamber. The soil respiration system consists of a soil respiration chamber (SRC) and an environmental gas monitor (EGM). For soil respiration, a chamber of known volume is placed on the soil and the rate of increase in CO_2 concentration within the chamber is monitored. With this system, the air is continuously sampled in a closed circuit through the EGM and the soil respiration rate is calculated, displayed and recorded by the analyzer. The air within the chamber is carefully mixed to ensure representative sampling without generating pressure differences, which would affect the evolution of CO_2 from the soil surface.

It is assumed that the rate of increase in CO_2 concentration is linear, though any leakage will cause a decline in its concentration with time. A quadratic equation is fitted to the relationship between the increasing CO_2 concentration and elapsed time. The flux of CO_2 per unit area and per unit time is measured using Equation (2):

$$R = \frac{(C_n - C_0)}{T_n} \times \frac{V}{A} \quad \dots(2)$$

where, R is the soil respiration rate (flux of CO_2 per unit area per unit time), C_0 is the CO_2 concentration at zero time i.e. $T=0$ and C_n is the concentration at the time T_n , A is the area of soil exposed, and V is the total volume of the chamber.

(3) Infra-red Analysis Method

Carbon dioxide can be sampled and analysed using infra red-based continuous soil CO_2 flux analyser (LI-8100). The LI-8100 system can be used with a 20 cm

short-term survey chamber to obtain soil CO₂ flux. The closed-chamber is placed on the soil and the rate of increase in CO₂ concentration in the chamber is used to determine the soil flux. CO₂ diffuses out of the soil in response to the concentration gradient between the soil pore spaces and the atmosphere. As CO₂ concentration in the chamber increases, the concentration gradient between soil and the chamber air decreases. This causes the measured soil CO₂ flux to decrease exponentially with time. The desired value of the soil flux can be determined when the concentration of CO₂ is same in the chamber and ambient atmosphere. The flux can be estimated using the initial slope of a fitted exponential curve at the ambient CO₂ concentration. This is done to minimize the impact of the altered CO₂ concentration gradient across the soil surface after chamber is closed.

(4) Closed Chamber Method

The CO₂ flux from the soil using closed-chambers can be determined by collecting gas samples periodically from the chambers and measuring the change in concentration of a gas with time during the period of linear concentration change similar to sampling of methane and nitrous oxide. The analysis can be done in gas chromatograph fitted with FID (discussed above) and a methanizer. The methanizer consists of a 6" × 1/8" stainless steel tube which is mounted alongside the edge of a heated valve oven, and thermostated to 380°C. The tube is packed with a special nickel/zinc/Pt-Pd catalyst powder. Column effluent is flushed with 20 mL/min of hydrogen prior to the methanizer entrance. Under these conditions, CO and CO₂ are converted to methane while passing through the methanizer. Hydrocarbons such as methane, ethane and propane pass through the methanizer unaffected. The CO and CO₂ being converted to methane, can be detected by the FID down to 1 ppm. The concentration of CO₂ is about 380 μL L⁻¹ in air, but CH₄ is only about 1.8 μL L⁻¹, the CO₂ response (after conversion to CH₄) on the FID is much stronger than of CH₄ (in air samples). Calculation of flux can be done similar to methane, as CO₂ is measured as methane. It may be noted that methanizer tubes can be poisoned by the large amounts of sulphur gases.

The CO₂ concentration in gas samples can also be analyzed using a gas chromatograph equipped with a thermal conductivity detector (TCD) and a Haysep D column 3-m long and 0.3-cm internal diameter. Helium is used as a carrier gas at a flow rate of 25 cm³ min⁻¹. Oven and detector temperatures are

50 °C and 150 °C, respectively. Standard CO₂ samples are used for calibration of the GC. Flux (F) of gases (g CO₂-C m⁻² day⁻¹) can be computed by Equation (3):

$$F = (\Delta g / \Delta t) (V / A) k \quad \dots(3)$$

where, $\Delta g / \Delta t$ is the linear change in CO₂ concentration inside the chamber (g CO₂-C m⁻³ min⁻¹); V is the chamber volume (m³); A is the surface area of the chamber (m²), and k is the time conversion factor (1440 min day⁻¹). Chamber gas concentration can be converted from molar mixing ratio (ppm) determined by GC analysis to mass per volume by assuming ideal gas relations. Hourly CO₂ fluxes are calculated from the time vs. concentration data using linear regression.

Global Warming Potential

The global warming potential (GWP) is an index developed to compare the strengths of different GHGs in reusing temperature on a common basis. CO₂ is used as the reference gas to compare the ability of a GHG to trap atmospheric heat relative to CO₂. Thus, GHG emissions are commonly reported as CO₂ equivalents (e.g. in tonnes of CO₂ eq.). The GWP is a time integrated factor, thus the GWP for a particular gas depends upon the time period selected. A 100-year GWP is the standard that has been broadly accepted for GHG reporting (Table 1). The GWP of agricultural soils may be calculated using Equation (4) (IPCC, 2007):

$$\text{GWP} = \text{CO}_2 + \text{CH}_4 * 25 + \text{N}_2\text{O} * 298 \quad \dots(4)$$

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Eddy Covariance Fluxes of Greenhouse Gases, Moisture and Heat from Soil

A Bhatia, N Jain, A Kumar and H Pathak

Introduction

Agricultural fields make significant contribution to greenhouse gas budget, especially wet low farmlands. The rice paddy fields are the major source of methane and uplands enriched with fertilizers emit nitrous oxide. Nitric oxides (NO_x) also contribute to production of GHG as a precursor of ozone (O₃). The global warming potential of CH₄ and N₂O are significantly higher than of CO₂. The global warming potential of CH₄ is 25-times and of N₂O is 298-times higher than CO₂ over a 100 years' time horizon (IPCC, 2007). Agricultural soils are the major sources of both these gases. The emissions of GHGs are highly influenced by the nitrogen status and the water content of the soil-crop system. Therefore, the current greenhouse gas budget of agricultural fields could be different from the estimated values earlier using limited scientific results.

The eddy covariance is a micrometeorological technique to measure vertical turbulent flux of water, carbon dioxide, heat, methane, nitrous oxide, ozone, nitrate and volatile organic components in the boundary layer of atmosphere. The eddy covariance (also known as eddy flux) technique provides a direct measure of the turbulent flux of a scalar across horizontal wind streamlines (Paw *et al.*, 2000). It is a statistical method used in the meteorology and other sectors that analyze high-frequency wind and scalar atmospheric data series, and yields values of fluxes of these properties.

Application of Eddy Covariance Fluxes

The eddy covariance (EC) technique is best applied over a flat terrain, when the environmental conditions are steady, and the underlying vegetation extends upwind for an extended distance. The EC flux measurements are often used to

estimate the integrated emission on a hectare scale with a continuous coverage in time (*see, Hendriks et al., 2008*). The technique is also used extensively for verification and tuning of global climate models, meso-scale and weather models, complex biogeochemical and ecological models, and remote sensing estimates from the satellites and aircrafts. The EC is potentially of immense use in many non-meteorological sciences, industrial monitoring, carbon storage and sequestration, and landfill and environmental management, and any type of monitoring of actual emission rates when energy, water or gas exchanges and balances are of interest. Data from flux sites help in testing physiological models of C-exchange and are critical to relating fluxes and remote sensing data. A combination of physiological and ecological measurements enables the partitioning of carbon fluxes into plant and soil components and reveals the mechanisms that are responsible for these fluxes. At some sites, biomass-based estimates of C storage have validated C budgets from direct flux data, and vice-versa. Data from the flux sites have been applied in ecology, weather forecasting, and climate studies, especially for sites with several years of data to quantify inter-annual flux variations. The important applications of eddy covariance flux tower in agricultural studies are:

- Gross Primary Production
- Ecosystem Respiration
- Net Primary Production (NPP)
- Trace Gas Emissions
- Hydrologic and Energy Partitioning
- Net Ecosystem Production (NEP)
- Biogeochemistry
- Greenhouse Gases Measurement

Greenhouse Gases Measurement

The methods generally employed to measure emissions of GHGs from soil are: closed-chamber method, open-chamber method, and micrometeorological method or the eddy covariance technique. Eddy covariance is the preferred technique for flux measurements since it is the only direct flux determination method as it has the advantage of continuous measurements from larger areas and short-term

variation of fluxes can be captured as compared to close chamber technique, limited information can be drawn on short-term variation due to discontinuous measurements from limited area (Meijide *et al.*, 2010).

Advantages of Eddy Covariance

- *In-situ* measurements over the area of interest
- Non-invasive sampling, causing no disturbance to the area over which fluxes are measured,
- Reliable, verifiable and defensible values of gas exchange or emission rates, and
- Automated measurement system providing continuous coverage with little intervention

Eddy Covariance Flux

Historical Development

It was in the early-1960s that researchers interested in measuring the exchange of energy and biologically important trace gases between plants and the atmosphere first began to employ aerodynamic methods on a regular basis. The basic idea was that by measuring the turbulent flux of heat, water vapor, CO₂, or momentum at some distance above a plant canopy, scientists could avoid the crippling sampling problems faced by them while aggregating measurements on individual leaves or from small patches of soil. Instead, they realized that the spatial averaging inherent in the atmospheric turbulence meant that a single measurement of the turbulent flux could provide the average biosphere-atmosphere exchange from an area of canopy equivalent to what is called as the instrument footprint. The problem was that direct measurement of the eddy flux of any of the properties of interest was very difficult.

An indirect alternative was, however, available. It was based on the assumption that the turbulent fluxes were proportional to the more readily-measured gradients of mean concentrations. This analogy with molecular diffusion was already well developed in fluid dynamics. In micrometeorology, it was combined with assumptions of similarity between transfer of momentum and scalars (Lemon and Wright, 1969) or just between different scalars, the so-called Bowen ratio approach, (Brown and Covey, 1966) to provide the first

aerodynamic methods of surface exchange measurement. Unfortunately, despite their widespread adoption, problems with these “gradient-diffusion” approaches were soon apparent (Raupach, 1979) and the search continued for ways to measure the turbulent fluxes directly.

Practical methods started with three-dimensional propeller anemometers and fast-response temperature sensors, but, by the late-1960s, sonic anemometers with their much smaller measuring volume and much better frequency response were becoming the instruments of choice. Initially, continuous-wave sonics were prone to serious drift of their mean levels and required constant attention during operations. As a result, their use was confined to intensive field campaigns. Analogous problems bedeviled the first rapid-response “open path” scalar sensors, which appeared in the 1970s and which relied on absorption of an infrared beam by H_2O or CO_2 molecules, but their promise was such that, by the mid-1980s, the future of surface-exchange measurements was clear. Continuous improvements in the accuracy and reliability of open path and closed path scalar sensors, especially of sonic anemometers, continued through the 1980s, and by the end of the decade eddy flux systems were being used for the continuous diurnal measurements of momentum, energy, and trace gasses in major campaigns like HAPEX and BOREAS.

In its early incarnations, this aerodynamic methodology was confined to steady conditions at sites chosen for their horizontal homogeneity. Under these conditions, the vertical turbulent flux, fairly close to the surface, could be equated to the surface-atmosphere exchange. Experiments conducted in ‘campaign mode’ allowed weeks of data to be rifled to find periods corresponding to such canonical conditions as in the famous Kansas and Minnesota experiments (Kaimal and Wyngaard, 1990). As the technique was extended to track exchange with the biosphere over the diurnal cycle, it was necessary to cope with non-stationarity of the eddy flux. It was manifested as the changes in total concentration of scalar in the air layer between the sensor and the surface, which meant that the vertical eddy flux at the sensor no longer equalled the surface exchange. It was particularly important when measuring over tall canopies such as the northern forests that were the focus of BOREAS. Measuring this “storage” term by an array of concentration sensors on the tower became an essential component of the eddy flux sensor even at the horizontally homogeneous sites.

Over the last decade, the aerodynamic technique has been regarded by the ecologists as a 'turnkey' system and is being adopted worldwide to make continuous measurements of land-atmosphere exchange from a wide range of biomes. Currently, there are more than 450 sites registered on the FLUXNET database (available online). The motivation for this massive effort is the need to understand and quantify the terrestrial carbon and water cycles and their likely future under the climate change.

These tower-based measurements provide one of the three pillars on which rests our understanding of the atmospheric pathway in the terrestrial carbon cycle. The others are large-scale concentration inversions and biomass assays. Ideally, these three methods operate naturally on different time and space scales, and are independent so that by using them we can triangulate gaps in our understanding. At the moment, however, biomass assays and models cannot be separated from aerodynamic measurements.

Two important flux tower networks, AmeriFlux (<http://cdiac.esd.ornl.gov/programs/ameriflux/>) and CARBOEUROPE (<http://www.bgc-jena.mpg.de/public/carboeur/carbo.html>) have been launched on the flux observation project at different types of ecosystem, including agricultural fields.

Principle

Eddy covariance requires measurements of 3-dimensional wind speed and gas concentration. High speed, high precision instruments are critical for rapid measurement of small changes in the air samples to accurately determine the flux.

Representation of Air Flow in Atmospheric Boundary Layer

Air flow can be imagined as a horizontal flow of numerous rotating eddies, that is, turbulent vortices of various sizes, with each eddy having horizontal and vertical components. The situation looks chaotic, but vertical movement of the components can be measured from the tower (Fig. 1).

Physical Concept of the Eddy Covariance

At one physical point on the tower, at Time1, Eddy1 moves parcel of air C_1 down at the speed W_1 . Then, at Time 2, Eddy 2 moves parcel C_2 up at the speed W_2 .

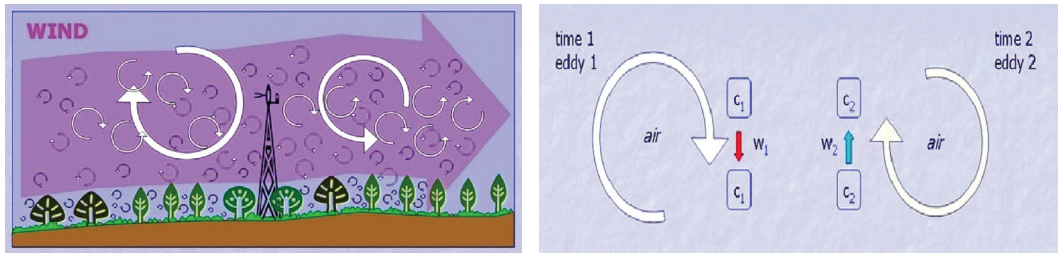


Figure 1. Air flow in the atmospheric boundary layer
(Source: Burba & Anderson, 2010)

Each parcel has a concentration, temperature, and humidity. If these factors, along with the speed are known, we can determine the flux. For example, if one knew how many molecules of water went down with eddies at Time 1, and how many molecules went up with eddies at Time 2, at the same point, one could calculate the vertical flux of water at this point over this time. So, vertical flux can be presented as a covariance of the vertical wind velocity and the concentration of the entity of interest.

Components of Eddy Covariance System

The major components of eddy covariance system are:

1. Greenhouse Gas Sensors
2. Air Temperature and RH Sensor
3. Wind Speed and Direction Sensors
4. Net Radiation Sensors
5. Surface Temperature Sensor
6. Canopy Temperature Sensor
7. Snow Depth Sensor
8. Soil Heat Flux Plates
9. TDR Probe (Time domain reflectometry)
10. Surface/ Soil Thermocouple Array
11. Barometric Pressure
12. Tree Bole & Xylem Temperature

13. Dataloggers
14. Data Acquisition, Transmission / Storage
15. Multiplexers Power Source
16. Tower/Tripod

Eddy Covariance Systems

A typical eddy covariance installation includes a CO₂/H₂O gas analyzer, 3-dimensional sonic anemometer, data storage unit, and power supply (Fig. 2). With the recent development of a low power, high precision methane analyzer, we can integrate methane measurements into the eddy covariance stations. In addition to high speed (>10 Hz), high precision instruments required by the eddy covariance system, it is also important that the system is flexible and allows easy integration of additional sensors when needed.

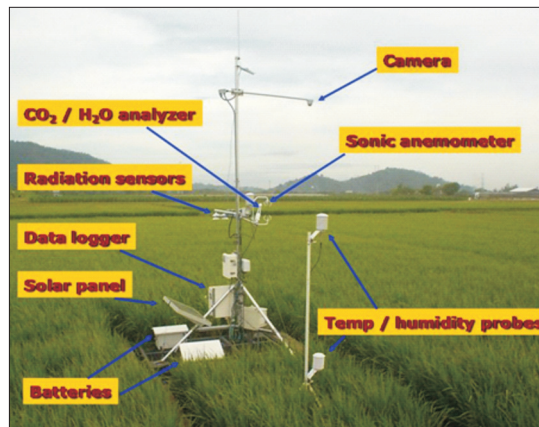


Figure 2. Eddy Covariance Flux Tower
(Courtesy: R Wassmann, IRRI, Philippines)

The eddy covariance method relies on the combined measurements of gas, temperature and wind speed to compute flux rates. While selecting instrumentation for eddy covariance research, one critical decision is whether to use an open path or closed path analyzer. Open and closed path instruments have certain advantages and disadvantages. For example, open path analyzers have lower power requirements than closed path analyzers, but closed path analyzers are less prone to interruptions caused by rainfall.

CO₂/H₂O Analyzer

Water vapour and carbon dioxide are the two most important green-house gases affecting global climate change. Fluxes of both of these gases can be measured directly, in a verifiable and defensible manner, using the eddy covariance method. Carbon dioxide flux measurements are required to assess carbon exchange and carbon emission rates, and to construct carbon budgets over natural, agricultural and urban ecosystems, as well as over industrial areas such as sequestration lands, landfills, feedlots, etc. These data could also be used to refine models of the global carbon cycle, to estimate carbon credits or footprints, or to verify compliance with regulations for carbon emissions.

Water vapor flux measurements are critical for a number of applications in precision agriculture such as water management, irrigation, and hydrological applications, agricultural and climate modelling, and remote sensing verification. Water vapour measurement is also important for computing eddy covariance fluxes of other atmospheric gases because it affects the measured densities of the gases, such as CO₂ and CH₄.

Calibration of the analyzer is done every 6 months against a dewpoint generator for water vapour and a standard gas for CO₂. Span values of two consecutive calibrations should usually differ by less than 3%.

Open Path Methane Analyzer

Methane is considered as the third most important greenhouse gas, after CO₂ and H₂O. In 2010, a low power open path methane analyzer made it possible to measure methane fluxes in regions not serviced by grid power. This solved the problem presented by earlier analyzers, which often required grid power to supply energy to the demanding vacuum pumps and temperature control systems. The use of such devices is geographically restricted, and in many remote regions, dynamics of methane is still not understood clearly as well as those of CO₂ and H₂O.

Several important methane-producing areas such as permafrost regions, rice fields, animal facilities, and landfills have not been studied so far. Widespread methane flux measurements are now possible and urgently needed in order to understand sources and sinks of atmospheric methane around the globe. A low power, high speed, high precision, self-cleaning methane analyzer is a big addition to an eddy covariance tower.

Sonic Anemometer

Vertical wind speed is a critical component of the eddy covariance method. In computation of fluxes, the vertical wind speed indicates the direction and the transport rate of energy, carbon dioxide, or other gases into or out of the ecosystem. In addition, the sonic anemometer measures air temperature, an important variable for flux computation.

Data Storage

Eddy covariance instruments generate large amounts of data. An analyzer interface unit is required that outputs data over the Ethernet, and also can store long-term data to a removable industrial-grade USB drive.

Power Supply

The electrical grid does not extend into most of the natural and agricultural environments. Instead, small photovoltaic power systems are often used to power eddy covariance systems. A well-designed photo-voltaic power system can deliver continuous power to an eddy covariance system, even in the cloudy regions.

Additional Sensors

Some eddy covariance systems may use additional sensors to provide supporting meteorological data. These sensors include:

- Net Radiometer – to measure total incoming and outgoing radiation, used to evaluate the energy balance
- Soil Heat Flux Plates
- Soil Temperature Sensors
- Soil Moisture Sensors
- Air Temperature and Relative Humidity Sensors
- Precipitation Sensors
- Quantum Sensor – to measure photo-synthetically active radiation
- Data Logger – for studies that use many sensors, an additional data storage device may be required

Software and Data Collection

Eddy covariance instruments are typically configured through the computer software. The software usually provides access to basic and advanced configuration options, as well as graphing of the live data stream. The software allows to:

- Configure sampling rate
- Configure auxiliary sensor inputs
- Select variables to log
- Set up data logging options

Every software has its own benefits depending on the requirements of the user, e.g., online versus off-line calculation of fluxes, graphical outputs, control tools, etc. However, the calculation and correction procedures should not differ between software packages that published by process the same raw data time series with identical conceptual assumptions. Presently, there are several software programs to process eddy covariance and derive quantities such as heat, momentum, and gaseous fluxes. Examples include EdiRe, ECpack, TSA, TK2, Alteddy, and EddySoft. Eddy covariance data sets are typically logged at 10 Hz (10 samples per second) in a regular ASCII text file format, which can be read in most spreadsheet applications.

Flux Calculations

Processing of eddy covariance data is accomplished using any of the multiple flux computation applications. Computation of fluxes includes checking of data for errors or gaps, aligning data to account for time delays, and computing fluxes based on half-hour or one hour averaging intervals.

Some major assumptions are the pre-requirement of the eddy covariance flux tower, which are as follows:

- Measurements at a point can represent an upwind area
- Measurements are done inside the boundary layer of interest
- Fluxes are measured only at the area of interest
- Flux is fully turbulent – most of the net vertical transfer is done by eddies
- Terrain is horizontal and uniform; the average of fluctuations is zero; density fluctuations are negligible; flow convergence and divergence are negligible

- Instruments can detect very small changes at high frequency, ranging from minimum of 5 Hz and to 40 Hz for tower-based measurements

Potential Errors

There are a number of potential flux errors introduced if not corrected due to assumptions, instrument problems, physical phenomena, and specifics of terrain.

The key errors in the measurement of flux are: Time response, Sensor separation, Scalar path averaging, Tube attenuation, High pass filtering, Low pass filtering, Sensor response mismatch, Digital sampling, Sensor time delay, Spike and noise, Unlevelled instrumentation, Density fluctuation, Sonic heat flux error, Band-broadening, Oxygen in 'krypton' path, Data filling. To minimize such errors, a number of procedures are adopted as given in Table 1.

Table 1. Error reason, range and remedy of the affected flux of eddy covariance flux tower

Errors reason	Affected flux	Range (%)	Remedy
Frequency response	All	5-30	Frequency response correction
Time delay	All	5-15	Adjusting for delay
Spike & noise	All	0-15	Spike removal
Unlevelled inst/flow	All	0-25	Coordinate rotation
Density fluctuation	H ₂ O, CO ₂ , CH ₄	0-50	Webb Pearman Leuning correction
Sonic heat error	Sensible heat	0-10	Sonic temperature correction
Band broadening	Mostly CO ₂ , CH ₄	0-5	Band broadening correction
O ₂ in path	Some H ₂ O	0-10	O ₂ correction
Missing data filling	All	0-20	Methodology/Test

Cost

The cost of eddy covariance system varies from Rs 90 to 110 lakhs depending upon quality of its components and the manufacturers. The cost of some of the components of eddy covariance flux tower is as follows: Data logger and software, (Rs 500,000), Three-axis anemometer (Rs 1,192,200), Open path CO₂/H₂O analyzer, (Rs 1,900,000); Air temperature and RH sensor, (Rs 79,000); Rain fall sensor, (Rs 32,000) and Enclosure, (Rs 41,000).

Measurements Using Eddy Covariance Flux Towers

Pattey *et al.* (2006) worked on tower-based N_2O flux measurements following liquid dairy manure applications over a forage field and a roving tower-based GHG flux measurement system was developed to monitor GHGs emissions from agricultural fields. The peak emissions were in the range of $10\text{--}15 \text{ mg } \text{N}_2\text{O}\text{--N m}^{-2} \text{ d}^{-1}$. The background N_2O emissions between the dairy manure applications were below $0.5 \text{ mg } \text{N}_2\text{O}\text{--N m}^{-2} \text{ d}^{-1}$ and did not exhibit any rainfall-driven emission pattern. The cumulative emissions following each liquid application were small, being below $0.4 \text{ kg } \text{N}_2\text{O}\text{--N ha}^{-1}$. During the following spring thaw, the emissions peak was $3 \text{ mg } \text{N}_2\text{O}\text{--N m}^{-2} \text{ d}^{-1}$, with cumulative emission over the period of $0.4 \text{ kg } \text{N}_2\text{O}\text{--N ha}^{-1}$.

Drewitt *et al.* (2009) have presented the initial results of a study of CO_2 isotope flux measurements over tilled and no-till agricultural surfaces. The CO_2 fluxes were measured in a soybean field in the Province of Buenos Aires, Argentina, with an eddy covariance system consisting of a $\text{CO}_2/\text{H}_2\text{O}$ infrared gas analyzer and a sonic anemometer by Posse *et al.* (2010). Loubet *et al.* (2010) have synthesized data of two years on measurement of CO_2 , CH_4 , N_2O , NO_x and O_3 exchange from a wheat-barley-mustard-maize rotation in Grignon (France). Meijide *et al.* (2010) have installed a Fast Methane Analyzer (Los Gatos Research Ltd.) in an eddy covariance field set-up in a Mediterranean rice paddy field in the Po Valley (Italy). Sintermann *et al.* (2010) have concluded that heating the inlet line to temperature above 100°C enabled NH_3 EC flux measurements.

Eddy covariance technique, networks are Fluxnet, Ameriflux, ICOS, CarboEurope, Fluxnet Canada, NEON, and iLEAPS. A Flux Tower was primarily used by the US Department of Agriculture / Forest Service as well as by the other government agencies to measure CO_2 , CH_4 and CO . The net ecosystem CO_2 exchange is presently measured at more than 30 sites in North America. Many of these research and monitoring sites are part of the AmeriFlux network. Flux towers are the integral parts of the North American Carbon Program, a multi-agency effort to measure and understand the sources and sinks of CO_2 , CH_4 , and CO in North America and in the adjacent ocean regions. Summed over the course of a month, season or year, data from these sites provide accurate measures of ecosystem CO_2 source or sink strengths. The flux towers provide information specific to one ecosystem type or condition. The multiple flux towers are being

installed in contrasting conditions to increase understanding about the effects of different treatments (e.g., harvesting), gradients of vegetation composition, or age chronosequences. Patel *et al.* (2011) have explored the utility of eddy covariance measurements for better understanding of CO₂ exchange over wheat and techniques for scaling of carbon fluxes using remotely sensed observations.

Indian subcontinent was not having any tower-based CO₂ flux measurement system so far. But now, the Indian Space Research Organization under its Geosphere Biosphere Programme is funding five eddy covariance towers for terrestrial CO₂ flux measurements in different ecological regions of the country. The planned tower sites are:

- (i) A mixed forest plantation (*Dalbergia sissoo*, *Acacia catechu*, *Holoptelia integrifolia*) at Haldwani in collaboration with DISAFRI, University of Tuscia, Italy and the Indian Council for Forestry Research and Education (ICFRE), Dehradun,
- (ii) A sal (*Shorea robusta*) forest in Doon valley in the Himalayan state of Uttarakhand in northern India,
- (iii) A teak (*Tectona grandis*) mixed forest at Betul in Madhya Pradesh in central India,
- (iv) An old teak plantation at Dandeli, and
- (v) A semi-evergreen forest at Nagarhole in Karnataka state in southern India.

Limitations

- It requires a continuum of high time resolution measurements (e.g. 5–20 Hz).
- The technique is mathematically complex, and requires significant care in setting up and processing data.
- These flux towers provide information specific to a single ecosystem type or condition.
- Flux data are noisy, and this uncertainty is largely due to random measurement error.
- There are a number of situations under which the EC method either could not be used to measure fluxes, or was not the best method to do so. These include environmental conditions with a very small area of study, predominantly low winds, complex terrain, point flux sources, etc. Also, for

some gases, such as ammonia and volatile compounds, the instrument system may not be sensitive enough to measure small changes at 10 Hz or 20 Hz frequencies.

- It requires a number of assumptions and corrections and demands a careful designing, execution and processing which is fit to the specific purpose at the specific experimental site.

Conclusions

The evidence of anthropogenic climate change is now unequivocal and the largest imponderables in predicting and preparing for its future course lie in estimating future emissions and the dynamics of terrestrial sinks. At present, the vast amount of information on the mechanism of the land sink that is latent in the terrestrial flux tower can only be accessed with confidence, where the aerodynamic measurements can be reinforced with other data. In other words, the eddy covariance flux tower is the best technique for measuring the flux of greenhouse gases from the agricultural fields. To understand the processes and mechanisms of agricultural ecosystem, carbon and water cycle and energy balance, eddy covariance is a promising technique.

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Greenhouse Gas Emission from Biomass Burning

N Jain, A Bhatia and H Pathak

Introduction

Burning of crop residues in fields is practised for clearing the land rapidly and inexpensively and allowing the tillage practices to proceed unimpeded by the residual crop material during preparations for the next growing season. The crops whose residues are normally burnt in India and in many other countries are rice, wheat, cotton, maize, millet, sugarcane, jute, pulses, rapeseed-mustard and groundnut. On burning, the crop residues are converted into gases such as carbon dioxide, methane, nitrous oxide, SO_x, NO_x, CO, soot and particulate matter, ash, aerosols, light hydrocarbons, volatile organic compounds (VOCs) such as benzene, and semi-volatile organic compounds (SVOCs) including polycyclic aromatic hydrocarbons (PAHs). The composition of the gases depends upon the burning conditions. Burning takes place in two phases: flaming and smoldering. During the flaming phase, concentration of carbon dioxide is more, whereas in the smoldering phase, concentration of carbon monoxide is more. Mainly there are three methods of sampling for gaseous and aerosol emissions from biomass burning.

(1) Ambient Sampling

It involves the measurement of GHGs/ other gaseous pollutant concentrations in the open atmosphere during the burning of biomass using steel canister/tedler bags, flow meter, and diaphragm sampling pump (Figure 1). The SUMA canister/tedler bags should be cleaned by flushing with nitrogen and evacuated prior to sampling. A fraction of air in each canister should be analyzed before use to ensure adequate cleaning.

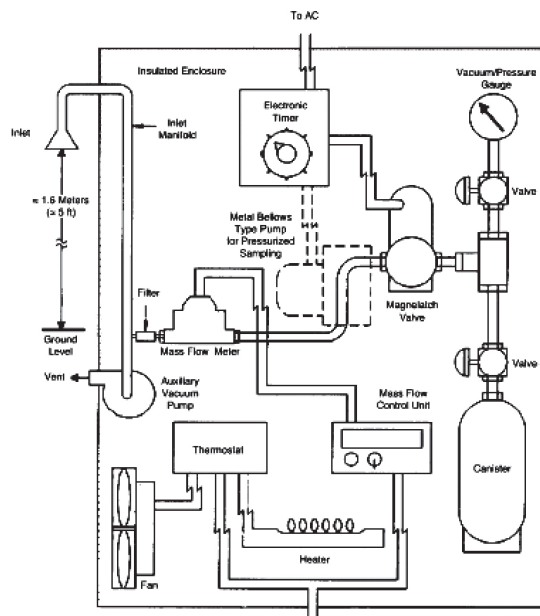


Figure 1. SUMMA canister and gas metering equipment for ambient sampling
(Source: Lemieux *et al.*, 2004)

(2) Plume Sampling (Nomad Sampler)

Direct sampling in the smoky plume of a fire is a difficult proposition. Many uncontrolled fires are not approachable by the sampling team. Temporal shifts in the position of the flame front and changes in wind directions make it difficult to position ambient sampling devices to collect a representative sample. To overcome these problems, EPA has developed the concept of a Nomad sampler. It is a hand held boom sampler which enables the sampling team to insert the suction end of a sampling probe directly into the smoke plume without going extremely close to the smoke or fire. The nomade consists of a TO-9 head and PUF/XAD/PUF (polyurethane foam/ no polar resin/ polyurethane foam) cartridge coupled with a high volume sampler, sampling train with scrubbers for SO_x, and NO_x. The TO-9 head is connected to the sampling inlet probe with an adapter. The sampling probe is supported by a light pole of 10 feet size to insert the probe into fire area conveniently during sampling (Figure 2). The gaseous samples can then be analyzed by GC or GCMS. The SO_x and NO_x samples can be analyzed by colorimetric methods.

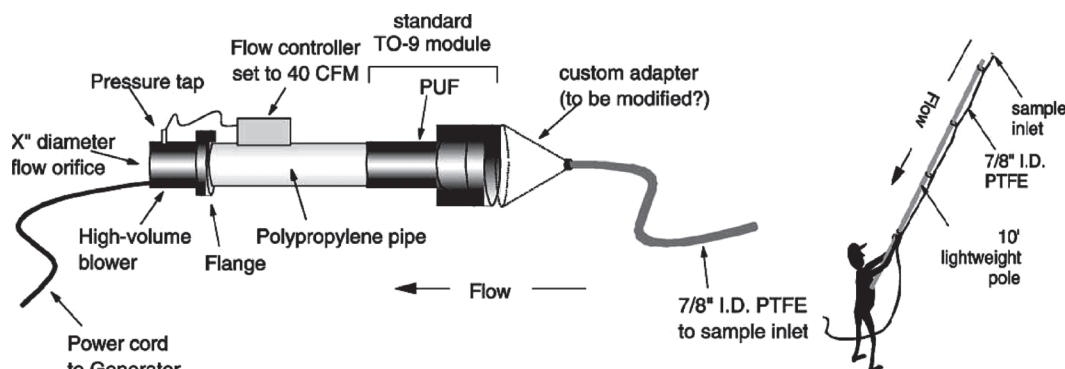


Figure 2. Nomad sampler
(Source: Lemieux *et al.*, 2004)

(3) Laboratory Simulation

Estimation of the amount of ash on the field after an open fire is difficult, since the ash may be dispersed on the ground by wind or flames. This is the most common method as the losses due to changing wind speed and wind direction are not there. Therefore, an effective way to develop emission factors for open burning sources is through laboratory simulations using a flux chamber approach. Measurement of emissions from the enclosed laboratory facility in combination with dilution rate of incoming air for combustion and loss in weight during combustion gives the emission factor as pollutant mass per unit of biomass burned. In flux chamber, small weighed quantity of the biomass to be burnt is combusted in the steel drum/ or a steel tray of the chamber (Figure 3). Air flow inside the chamber can be controlled with the help of flow meters attached to the air passage. Gas sample can be collected with the help of a sampling probe, a filter holder, a pump, and a Tedlar bag/steel canister from the sample duct. The filters should be dried in oven at 70-80 °C for 24 hours and stored in desiccators prior to sampling. Tedlar bags/steel canisters should be flushed at least three-four times with clean air or nitrogen before use and sealed at the end of the sampling period. Air samples are then taken from the tedlar bags/steel canisters using air tight glass syringes and injected into a gas chromatograph (GC) fitted with ECD for nitrous oxide and FID for methane and FID with methaniser carbon dioxide analysis. Measurements of the mass of burning material, combustion air and dilution air flow rates, and temperatures should also be noted. The GHGs

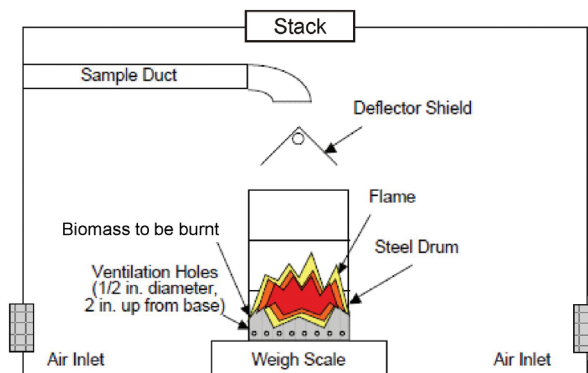


Figure 3. Laboratory simulations flux chamber
(Source: Lemieux *et al.*, 2004)

concentrations measured in the chamber can be converted to the mass emissions of individual GHGs (emission factor units) using the following equation:

$$EF = (C_{\text{sample}} * Q_{\text{chamber}} * t) / M_{\text{burned}}$$

where, EF = Emission factor in mg/kg biomass consumed, C_{sample} = Concentration of the GHG in the sample (mg/m^3), Q_{chamber} = Flow rate of dilution air into the chamber (m^3/min), t = Burning time of sample in minutes, and m = Mass of biomass burnt (kg).

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Inventory of Methane and Nitrous Oxide Emissions from Agriculture

A Bhatia, N Jain and H Pathak

Introduction

The atmospheric concentration of both methane (1774 ppb) and nitrous oxide (319 ppb) has increased markedly world over as a result of human activities. The observed increase in concentrations of methane and nitrous oxide is predominantly due to agriculture and use of fossil fuel. Globally, agriculture contributes about 60% of nitrous oxide and 50% of methane emissions. Agricultural methane and nitrous oxide emissions increased by 17% from 1990 to 2005 (Smith, 2007). The three major sources of global methane and nitrous oxide emissions from the agriculture sector are: Soil (38% of $\text{CH}_4 + \text{N}_2\text{O}$), Rice production (11% of CH_4) and Biomass burning (12% of $\text{CH}_4 + \text{N}_2\text{O}$).

Inventory of Methane Emission from Rice Fields

Rice fields with anaerobic conditions in wetlands as a result of soil submergence under water are one of the major sources of methane emission. Decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes into the atmosphere primarily by vascular transport through the rice plants. The volume of CH_4 emitted from a given area of rice is a function of the crop duration, water regimes and organic soil amendments. The CH_4 emissions are estimated by multiplying the seasonal emission factors by the annual harvested area. Harvested area for each sub-unit (state) on multiplication with the respective emission factor is the representative of conditions that define the sub-unit (state). The total annual emissions are equal to the sum of emissions from each sub-unit of harvested area using Equation (1):

$$\text{CH}_4 \text{ Rice} = \sum_{i,j,k} (\text{EF}_{i,j,k} \cdot A_{i,j,k} \cdot 10^{-6}) \quad \dots(1)$$

where, CH_4_{Rice} = Annual methane emissions from rice cultivation ($Gg\ CH_4\ yr^{-1}$); EF_{ijk} = Seasonal integrated emission factor for i, j, and k conditions ($kg\ CH_4\ ha^{-1}$); A_{ijk} = Annual harvested area of rice for i, j, and k conditions ($ha\ yr^{-1}$); i, j, and k = Different ecosystems, water regimes, type and amount of organic amendments, under which CH_4 emissions from rice may vary. Separate calculations are undertaken for each rice ecosystems (viz., irrigated, rainfed, and deep water rice production).

The baseline emission factor is scaled for organic amendments and water regime in rice ecosystems according to Equation (2):

$$EF_i = EF_c \bullet SF_w \bullet SF_p \bullet SF_o \quad \dots(2)$$

where,

EF_i = Adjusted seasonal emission factor for a particular harvested area (state)

EF_c = Baseline emission factor for continuously flooded fields without organic amendments. A baseline emission factor for not flooded fields for less than 180 days prior to rice cultivation and continuously flooded during the rice cultivation period without organic amendments (EF_c) is used as a starting point. The IPCC default for EF_c is $1.30\ kg\ CH_4\ ha^{-1}\ day^{-1}$ (with error range of 0.80 - 2.20).

SF_w = Scaling factor to account for the differences in water regime during the cultivation period.

SF_p = Scaling factor to account for the differences in water regime in the pre-season before the cultivation period

SF_o = Scaling factor for the type and amount of organic amendments applied. (More CH_4 is emitted from amendments containing higher amounts of easily decomposable carbon and emissions also increase as more of each organic amendment is applied. The scaling factor should be based on the application rate of organic amendment and also its conversion factor.)

Uncertainties in Methane Emission

The uncertainties associated with the estimation of CH_4 emissions are quite significant. These uncertainties arise due to differing conditions such as climate, agronomic practices, and soil properties. Various physical, chemical and biological properties of soil influence formation of CH_4 in soil. Uncertainties in emission

factors primarily arise due to different soil types, rice cultivars used and also the different agronomic practices of water, fertilizer and manure management. Uncertainty is also associated with the duration of different rice varieties used in a state. The most popular cultivar of a region will have to be identified based on the area under its cultivation and also on expert judgment. Maximum uncertainty will be associated with this factor.

Timing of application of organic amendment especially rice straw incorporation may lead to uncertainty. Uncertainties also arise due to non-availability of harvested area under each water regime and type of organic amendment in a particular rice ecosystem. Most likely, activity data will be more reliable as compared to the accuracy of the emission factors.

Inventory of Nitrous Oxide Emissions from Managed Soils

Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. One of the main controlling factors in this reaction is the availability of inorganic N in the soil. This methodology, therefore, estimates N_2O emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilizers, deposited manure, crop residues, sewage sludge), or of mineralization of N in soil organic matter following drainage/management of organic soils, or cultivation/land-use change on mineral soils.

The emissions of N_2O that result from anthropogenic N inputs or N mineralization occur through both (a) direct pathway (i.e., directly from the soils to which the N is added/released), and (b) indirect pathways: (i) following volatilization of NH_3 and NO_x from managed soils and from fossil fuel combustion and biomass burning, and the subsequent redeposition of these gases and their products NH_4^+ and NO_3^- to soils and waters; and (ii) after leaching and runoff of N, mainly as NO_3^- , from managed soils.

The total emissions of N_2O from managed soils are estimated using Equation (3):

Total N₂O- N Emission

$$N_2O-N_{TOTAL} = N_2O-N_{DIRECT} + N_2O-N_{INDIRECT} \quad \dots(3)$$

Direct emissions of N₂O from managed soils are estimated separately from indirect emissions, though using a common set of activity data.

In most soils, an increase in available N enhances nitrification and denitrification rates which then increase the production of N₂O. Increases in available N can occur through human-induced N additions or change of land-use and/or management practices that mineralize soil organic N.

The following N sources are included in the methodology for estimating direct and indirect N₂O emissions from managed soils:

- Synthetic N fertilizers (F_{SN});
- Organic N applied as fertilizer (e.g., animal manure, compost, sewage sludge) (F_{ON});
- Urine and dung N deposited as manure (F_{PRP});
- N in crop residues (above-ground and below-ground), including from N-fixing crops (F_{CR});
- N mineralization associated with loss of soil organic matter resulting from management of mineral soils (F_{SOM}); and
- Drainage/management of organic soils (i.e., Histosols) (F_{OS}).

Direct N₂O Emissions

For estimating direct N₂O emissions from managed soils, Equation (4) is used:

$$N_2O_{Direct} - N = N_2O - N_{N\text{ inputs}} + N_2O - N_{OS} + N_2O - N_{CAS} \quad \dots(4)$$

where,

$$N_2O - N_{N\text{ inputs}} = \{([F_{SN} + F_{ON} + F_{CR} + F_{SOM}] * EF_1) + ([F_{SN} + F_{ON} + F_{CR} + F_{SOM}]_{FR} * EF_{1FR})\}$$

$$N_2O - N_{OS} = ([F_{OS,CG,Temp} * EF_{2\text{ CG, Temp}}] + [F_{OS,CG,Trop} * EF_{2\text{ CG, Trop}}])$$

$$N_2O - N_{CAS} = [F_{CAS} * EF_{3\text{ CAS}}]$$

where,

$$N_2O_{Direct} - N = \text{Annual direct } N_2O - N \text{ emissions produced from managed soils (kg } N_2O - N \text{ yr}^{-1}\text{)}$$

$N_2O-N_{N \text{ inputs}}$ = Annual direct N_2O-N emissions from N inputs to managed soils (kg N_2O-N yr⁻¹)

N_2O-N_{OS} = Annual direct N_2O-N emissions from managed organic soils (kg N_2O-N yr⁻¹)

N_2O-N_{CAS} = Annual direct N_2O-N emissions from urine and dung inputs by cattle to agricultural soils (kg N_2O-N yr⁻¹)

F_{SN} = Annual amount of synthetic fertilizer N applied to soils (kg N yr⁻¹)

F_{ON} = Annual amount of animal manure, compost, and other organic N additions applied to soils (Note: N_2O emissions from the N in sewage sludge are accounted for in waste sector) (kg N yr⁻¹)

F_{CR} = Annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, returned to soils (kg N yr⁻¹)

F_{SOM} = Annual amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management (kg N yr⁻¹)

F_{OS} = Annual area of managed/drained organic soils (ha) (Note: the subscripts CG, Trop refer to Cropland and Tropical, respectively)

F_{CAS} = Annual amount of urine and dung N deposited by animals (cattle) when performing jobs on agricultural soils (kg N yr⁻¹) (Note: the subscripts C refer to cattle)

EF_1 = Emission factor for N_2O emissions from N inputs (kg N_2O-N) (kg N input⁻¹)

EF_{1FR} = Emission factor for N_2O emissions from N inputs to flooded rice, kg N_2O-N (kg N input)⁻¹

EF_2 = Emission factor for N_2O emissions from drained/managed organic soils (kg N_2O-N ha⁻¹ yr⁻¹)

EF_{3CAS} = Emission factor for N_2O emissions from urine and dung N deposited on agricultural soils by animals (cattle used for agricultural jobs), kg N_2O-N (kg N input⁻¹)

Choice of Activity Data*Applied Synthetic N Fertiliser (F_{SN})*

The term F_{SN} refers to the annual amount of synthetic N fertiliser applied to soils. It is estimated from the total amount of synthetic fertiliser consumed annually. The fertiliser consumption data may be collected from *Fertilizer Statistics*, published by Fertilizer Association of India, New Delhi.

Applied Organic N Fertiliser (F_{ON})

The applied organic N fertiliser (F_{ON}) refers to the amount of organic N inputs applied to soils other than by grazing animals and is calculated using Equation (5). This includes manure and compost applied to soils. Sewage sludge is generally accounted for in the waste sector.

$$F_{ON} = F_{AM} + F_{COMP} + F_{GM} \quad \dots(5)$$

where,

F_{ON} = Total annual amount of organic N fertiliser applied to soils other than by grazing animals (kg N yr⁻¹)

F_{AM} = Annual amount of animal manure N applied to soils (kg N yr⁻¹)

F_{COMP} = Annual amount of total compost N applied to soils (kg N yr⁻¹)

F_{GM} = Amount of green manure nitrogen (kg N yr⁻¹ applied to soils annually). (Addition of N through green manure crops (N_{GM}) such as sesbania (*Sesbania aculeata*) and sun hemp (*Crotalaria juncea*), etc. is included here).

The term F_{AM} is determined by adjusting the amount of manure N available (calculated from livestock population) for the amount of managed manure used for feed ($Frac_{FEED}$), burnt for fuel ($Frac_{FUEL}$), or used for construction ($Frac_{CNST}$), as shown in Equation (6). The categories of livestock include cattle, buffalo, sheep, goat, camel, poultry etc.

$$F_{AM} = N_{MMS_{Avb}} \cdot (1 - Frac_{FEED} + Frac_{FUEL} + Frac_{CNST} + Frac_{COLLEC}) \quad \dots(6)$$

where,

- F_{AM} = Annual amount of animal manure N applied to soils (kg N yr⁻¹)
 N_{MMS_Avb} = Amount of managed manure N available for soil application, feed, fuel or construction (kg N yr⁻¹)
 $Frac_{FEED}$ = Fraction of managed manure used for feed,
 $Frac_{FUEL}$ = Fraction of managed manure used for fuel,
 $Frac_{CNST}$ = Fraction of managed manure used for construction, and
 $Frac_{COLLEC}$ = Fraction of managed manure lost during collection of dung.

Urine and Dung from Grazing Animals (F_{PRP})

It is estimated using Equation (7) from the number of cattle $N_{(C)}$ that is used on agricultural soils, the annual average amount of N excreted by cattle $Nex_{(C)}$, and the fraction of this N deposited on soils $MS_{(C)}$.

$$F_{PRP} = [N_{(C)} * Nex_{(C)} * MS_{(C)}] \quad \dots(7)$$

where,

- F_{PRP} = Annual amount of urine and dung N deposited by cattle (kg N yr⁻¹)
 $N_{(C)}$ = Number of cattle used for agricultural jobs in the country,
 $Nex_{(C)}$ = Annual average N excretion per head of cattle used for agricultural jobs in the country (kg N animal⁻¹ yr⁻¹), and
 $MS_{(C)}$ = Fraction of total annual N excretion for cattle that is deposited while performing agricultural jobs.

Crop Residue N, including N-fixing Crops and Forage, Returned to Soils (FCR)

The term FCR refers to the amount of N in crop residues (above-ground and below-ground), including N-fixing crops, returned to soils annually (Eq. 8).

$$F_{CR} = \sum_T \{ Crop_{(T)} * (Area_{(T)} - Area_{burnt(T)} * C_l) * Frac_{Renew(T)} * [R_{AG(T)} * N_{AG(T)} * (1 - Frac_{Remove(T)}) + R_{BG(T)} * N_{BG(T)}] \} \quad \dots(8)$$

where,

- F_{CR} = Annual amount of N in crop residues (above and below ground), including N-fixing crops, returned to soils annually (kg N yr⁻¹)

$Crop_{(T)}$ = Harvested annual dry matter yield for crop T (kg d.m. ha⁻¹)

$Area_{(T)}$ = Total annual area harvested of crop T (ha yr⁻¹)

$Area\ burnt_{(T)}$ = Annual area of crop T burnt (ha yr⁻¹),

C_f = Combustion factor (dimensionless)

$Frac_{Renew\ (T)}$ = Fraction of total area under crop T that is renewed annually. For annual crops $Frac_{Renew} = 1$

$R_{AG(T)}$ = Ratio of above-ground residues dry matter ($AG_{DM(T)}$) to harvested yield for crop T ($Crop(T)$) (kg d.m.) (kg d.m.)⁻¹,

$$= AG_{DM(T)} \times 1000 / Crop_{(T)}$$

$N_{AG(T)}$ = N content of above-ground residues for crop T, kg N(kg d.m.)⁻¹.

$Frac_{Remove(T)}$ = Fraction of above-ground residues of crop T removed annually for purposes such as feed, bedding and construction, kg N (kg crop-N)⁻¹.

$R_{BG(T)}$ = ratio of below-ground residues to harvested yield for crop T, kg d.m. (kg d.m.)⁻¹.

$N_{BG(T)}$ = N content of below-ground residues for crop T, kg N (kg d.m.)⁻¹

T = Crop type

$Frac_{NCRST}$ = Nitrogen content of residues of different crops. Major non-N fixing crops and N-fixing crops such as tur, gram, groundnut soybean, and other *rabi* and *kharif* pulses, may be taken for the calculation.

Mineralized N Resulting from Loss of Soil Organic C Stocks in Mineral Soils through Land-use or Management Practices (F_{SOM})

The term F_{SOM} refers to the amount of N mineralized from loss in soil organic C in mineral soils through change of land-use or management practices. If loss in soil C occurs, it will be accompanied by a simultaneous mineralization of N. This mineralized N is regarded as an additional source of N available for conversion to N₂O just as mineral N released from decomposition of crop residues, for example, becomes a source.

The same default emission factor (EF_1) is applied to mineralized N from soil organic matter loss as is used for direct emissions resulting from fertiliser and organic N inputs to agricultural land. This is because the ammonium and nitrate resulting from soil organic matter mineralization is of equal value as a substrate for the microorganisms producing N_2O by nitrification and denitrification, no matter whether the mineral N source is soil organic matter loss from land-use or management practice change, decomposition of crop residues, synthetic fertilizers or organic amendments.

$$F_{SOM} = \sum_{LU} [(\Delta C_{MINERAL, LU} * \frac{1}{R}) * 1000] \quad \dots(9)$$

where,

F_{SOM} = Net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through change in land-use or management practices (kg N)

$\Delta C_{Mineral, LU}$ = Average annual loss of soil carbon for each land-use type (LU), tonnes C, and

R = C:N ratio of the soil organic matter.

The amount of N mineralized can be calculated from the decomposition of soil organic carbon (SOC).

Nitrous oxide emission (N_2O -N ha^{-1}) due to mineralization of organic N from soil into inorganic pool (NH_4^+) may be calculated in relation to mineralization of C using Equation (10) (Pathak and Wassmann, 2007).

$$N_2O-N = SOC \times 1000 \times 45 \times BD \times 0.000085 / 10 \times 365 \times 0.0024 \quad \dots(10)$$

where, SOC is soil organic C (%), 1000 and 45 are the coefficients used to calculate the weight of soil up to 45 cm depth, BD is soil bulk density ($Mg\ m^{-3}$), 10 is the C:N ratio of soil organic matter, 0.000085 is the rate of mineralization (Seligman and van Keulen, 1981), 365 is duration (days) and 0.0024 is rates of nitrification and denitrification ($kg\ kg^{-1}$). A similar approach can be used in the denitrification and decomposition (DNDC) model for estimating N_2O emission from soil (Li, 2000).

Area of Drained/Managed Organic Soils (F_{OS})

The term FOS refers to the total annual area (ha) of drained/managed organic soils. F_{OS} is the area of organic soils harvested (area of organic soils cultivated annually). Organic soils are those soils, which contain more than 12-18% organic carbon depending upon the clay content. Indian soils are deficient in organic carbon, which is less than 1%. Only some cultivated soils of Kerala and northeast hill regions contain higher organic carbon (say about 5%).

Emission Factor for Nitrous Oxide Emissions

The EF_1 is the emission factor for N_2O -N emitted from various nitrogen additions to soil. According to IPCC (2006), EF_1 has a default value of 1%. EF_1 based on the studies conducted in India (Kumar *et al.*, 2000a;b ; Majumdar *et al.*, 2000; Pathak *et al.*, 2002; Ghosh *et al.*, 2002; Bhatia *et al.*, 2005), has been calculated as 0.7%.

Indirect N_2O Emission

Emissions of N_2O also take place through two indirect pathways of volatilization and leaching (mentioned above).

$$N_2O_{\text{indirect}} = N_2O_{(ATD)} + N_2O_{(L)}$$

where,

N_2O_{indirect} denotes the emission of N_2O -N indirectly from agriculture.

Volatilization $N_2O_{(ATD)}$

The N_2O emissions from atmospheric deposition of N volatilized from managed soil are estimated using Equation (11):

$$N_2O_{(ATD)} - N = [(F_{SN} \cdot \text{Frac}_{GASF}) + \{(F_{ON} + F_{PRP}) \cdot \text{Frac}_{GASM}\}] \cdot EF_3 \quad \dots(11)$$

where,

$N_2O_{(ATD)} - N$ = Annual amount of N_2O -N produced from atmospheric deposition of N volatilized from managed soils (kg N_2O -N yr^{-1});

F_{SN} = Annual amount of synthetic fertilizer N applied to soils (kg N yr^{-1});

$Frac_{GASF}$ = Fraction of synthetic fertilizer that volatilizes as NH_3 and NO_x , kg N volatilized (kg of N applied)⁻¹. Extents of volatilization, however, depend on several of soil, management, plant and climatic factors like the amount of N applied, soil pH, temperature and moisture.

F_{ON} = Annual amount of managed animal manure, compost, other organic N additions applied to soils, kg N yr⁻¹

F_{PRP} = Annual amount of dung N deposited by animals during grazing, kg N yr⁻¹

$Frac_{GASM}$ = Fraction of applied organic N fertilizer materials (F_{ON}) and dung N deposited during grazing that volatilizes as NH_3 and NO_x , kg N volatilized (kg of N applied or deposited)⁻¹.

EF_3 = Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N- N_2O (kg NH_3 -N + NO_x -N volatilized)⁻¹]. This value is 1% as per IPCC (2006) default value.

$\sum (N_{(T)} * Nex_{(T)})$ = Amount of animal manure nitrogen excreted annually.

Leaching/Runoff, $N_2O(L)$

The N_2O emissions from leaching and runoff in regions where leaching and runoff occur are estimated using Equation (12):

$$N_2O_{(L)} - N = F_{SN} + F_{ON} + F_C + F_{CR} + F_{SOM} \bullet Frac_{LEACH-(H)} \bullet EF_4 \quad \dots(12)$$

where,

$N_2O_{(L)} - N$ = Annual amount of N_2O -N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O -N yr⁻¹,

F_{SN} = Annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs, kg N yr⁻¹,

F_{ON} = Annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, kg N yr⁻¹,

- F_C = Annual amount of urine and dung N deposited by cattle performing agricultural jobs in regions where leaching/runoff occurs, kg N yr⁻¹,
- F_{CR} = Amount of N in crop residues (above- and below-ground), including N-fixing crops, returned to soils annually in regions where leaching/runoff occurs, kg N yr⁻¹,
- F_{SOM} = Annual amount of N mineralized in mineral soils associated with loss of soil C from soil organic matter as a result of changes in land-use or management practices in regions where leaching/runoff occurs, kg N yr⁻¹,
- $Frac_{LEACH-(H)}$ = Fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)⁻¹
- EF_4 = Emission factor for N₂O emissions from N leaching and runoff, kg N₂O–N (kg N leached and runoff)⁻¹.

Emission Factors for Volatilization and Leaching

Indigenous values for emission factors associated with volatilized and re-deposited N (EF_3), and associated with N lost through leaching/runoff (EF_4) are used. Since data across the country is not available, expert judgment may be used for deriving the emission factors. Uncertainties in emission factors are likely to be more than in the case of activity data.

$$\text{Total N}_2\text{O-N emission} = \text{N}_2\text{O-N}_{\text{DIRECT}} + \text{N}_2\text{O-N}_{\text{INDIRECT}} \quad \dots (13)$$

Uncertainties in Nitrous Oxide Emissions

The uncertainties associated with estimation of N₂O emission are quite significant (IPCC, 2006). Various physical, chemical and biological properties as well as crop management practices influence diffusion of N₂O from soil to air. Different agricultural management practices *per se* have different impact on N₂O emission. It is not possible to quantify N₂O emission easily at large scales. So generally field level data are used to upscale to regional, national and global levels using default emission factors, and the methodologies recommended by the IPCC. The

method suggested by IPCC is very simple and does not take into account agro-climatic factors of different regions which generally influence emission of these gases.

The up-scaling processes that depend highly on the models and database are responsible for about 63% uncertainties (Xuri, 2003). Moreover, the timings and mode of fertilizer application have a strong influence on N₂O emission from soil. IPCC currently assumes a N₂O emission factor of 1% of the N applied to soils or released through activities that result in mineralization of organic matter in mineral soils. The uncertainty range in this emission factor is 0.003 - 0.03%.

Methodology for Estimating Non-CO₂ Emissions from Crop Residue Burning

Currently, wastes from nine crops, *viz.* rice, wheat, cotton, maize, millet, sugarcane, jute, rapeseed-mustard and groundnut, are subjected to burning. The amount of agricultural wastes produced by a country depends on its crop management system. Non-CO₂ emissions from crop residue burning may be calculated using Equation (14):

$$L_{\text{fire}} = A \bullet M_B \bullet C_f \bullet G_{\text{ef}} \bullet 10^{-3} \quad \dots (14)$$

where,

L_{fire} = Amount of non-CO₂ greenhouse gas emissions from fire, tons of each GHG
e.g., CH₄, N₂O, etc.

A = Area burnt, ha

M_B = Mass of crop residue available for combustion, tons ha⁻¹.

C_f = Combustion factor, dimensionless (default values will be used)

G_{ef} = Emission factor, g kg⁻¹ dry matter burnt (default values will be used)

The combustion factor is a measure of the proportion of the fuel (crop residue in our case) that is actually combusted, which varies as a function of the size and architecture of the fuel load, the moisture content of the fuel and the type of fire

(i.e., intensity and rate of spread which is markedly affected by climatic variability and regional differences).

G_{ef} is the emission factor and it gives the amount of a particular greenhouse gas emitted per unit of dry matter combusted, which can vary as a function of the carbon content of the biomass and the completeness of combustion. For species with high N concentrations, NO_x and N₂O emissions from fire can vary as a function of the N content of the fuel.

Choice of Activity Data

Activity data include estimates of land areas under the crop types for which agricultural residues are normally burnt. The amount of fuel available may be estimated from crop production statistics and the ratio of crop yield to the residue produced.

Choice of Emission Factors

Indigenously developed emission factors should be used. But in the absence of such data, the default emission coefficients based on emission factors given by Andreae and Merlet (2001) may be used.

Uncertainty in Emission from Crop Residue Burning

Estimates of the area planted under each crop type for which residues are normally burnt may be highly uncertain. In India, the primary end-uses of crop residues are as animal fodder, industrial and domestic fuel, material for thatching, packaging, bedding, construction of walls/fences, and as green-manure and compost. The amount left is what is available for field burning, and only a fraction of this amount is actually subject to burning. This fraction is, in fact, highly uncertain and varies with local and regional climate, season, livestock distribution, availability of fuel wood, availability of fodder, weed infestation, etc. The total dry residue generation in the year 1994 was about 203 thousand tonnes. Using IPCC emission coefficients, the CH₄ released from this source was found to be about 167 Gg (NATCOM, 2004). In India, about 60% of households depend on traditional sources of energy, like fuel wood, dung cake and crop residue for meeting their cooking and heating needs. High uncertainties are associated with

this estimate as biomass activity data are based only on small surveys carried out at different points of time. More exhaustive surveys are required to establish the quantity of various types of biomass used in the country.

A Case Study

A state-wise inventory of methane, nitrous oxide and non-CO₂ GHGs emissions from agricultural soils of India was prepared for the base year 2000 using the above inventory preparation guidelines. All activity data were taken from *Agricultural Statistics*. The emission coefficients used in the inventory are listed in Table 1. State-specific emission coefficients from all major rice ecosystems were used for estimating the methane emissions. In the case of nitrous oxide, both direct and indirect emissions from agricultural soils in different states were calculated using indigenous emission factors. Indian rice fields covering an area of 44.7 million ha emitted 3.5 million tons of CH₄ (Table 2).

Table 1. Coefficients used in preparation of inventory

Parameter	Default IPCC coefficients	Coefficients present inventory
EF _c , seasonally integrated emission factor for continuously flooded fields	200 kg ha ⁻¹	State specific coefficients
EF ₁ (N ₂ O emission from applied fertilizer) (%)	1	0.58
EF ₃ (N ₂ O emission from volatilized N from fertilizer and manure) (%)	1	0.5
EF ₄ (N ₂ O emission from leached and run-off N from fertilizer and manure) (%)	2.5	0.5
Frac _{GASF} (Gas loss through volatilization from inorganic fertilizer) (%)	10	15
Frac _{GASF-AM} (Gas loss through volatilization from manure) (%)	20	15
Frac _{leach} (Leaching loss of N from applied fertilizer and manure) (%)	30	10

Table 2. Methane emission coefficients from different rice ecosystems in the year 2000

Ecosystem	Water Regime*	Rice Area (M ha)	Emission coefficient (kg ha ⁻¹)	Methane emission (Gg)
Irrigated	CF	6.85	162	1138
	SA	8.99	66	605
	MA	9.49	18	144
Rainfed	DP	8.66	66	550
	FP	4.35	190	827
Deep water	DW	1.37	160	217
Upland		4.83	0	0
Total		44.7		3483

*CF- Continuously flooded, SA- Single aeration, MA- Multiple aeration, DP –Drought prone, FP- Flood-prone, DW- Deep water

For the base year 2000, the direct and indirect nitrous oxide emissions from Indian agricultural soils were estimated to be 98.3 Gg (29.3 Tg CO₂ eq) and 16.2 Gg (4.8 Tg CO₂eq), respectively (Table 3). Emissions from field burning of agricultural residues in the year 2000 resulted in 223 Gg of CH₄ and 5.8 Gg of N₂O (Table 4).

Table 3. State-wise direct and indirect nitrous oxide and methane emissions and their global warming potential (CO₂ equivalents) for the year 2000

State	Direct N ₂ O-N (Gg)	Indirect N ₂ O-N (Gg)	Total N ₂ O-N (Gg)	Total N ₂ O (Gg)	CH ₄ (Gg)	GWP (CO ₂ eq. Tg)
Andaman & Nicobar Islands	0.01	0.00	0.01	0.02	0.76	0.02
Andhra Pradesh	11.19	1.95	13.14	20.65	422.79	16.73
Arunachal Pradesh	0.02	0.00	0.02	0.03	2.29	0.07
Assam	0.89	0.11	1.00	1.57	194.23	5.32
Bihar	5.35	0.97	6.32	9.93	388.23	12.67
Chhattisgrah	0.84	0.08	0.92	1.45	239.07	6.41
Dadra & Nagar Haveli	0.01	0.00	0.01	0.02	0.94	0.03
Delhi	0.04	0.01	0.05	0.08	0.12	0.03

Contd...

Table 3 contd.....

State	Direct N ₂ O-N (Gg)	Indirect N ₂ O-N (Gg)	Total N ₂ O-N (Gg)	Total N ₂ O (Gg)	CH ₄ (Gg)	GWP (CO ₂ eq. Tg)
Daman & Diu	0.00	0.00	0.00	0.00	0.14	0.00
Goa	0.05	0.01	0.06	0.09	3.87	0.12
Gujarat	4.51	0.71	5.22	8.20	42.05	3.50
Haryana	5.28	0.95	6.23	9.79	67.19	4.60
Himachal Pradesh	0.62	0.11	0.73	1.15	1.04	0.37
Jammu & Kashmir	0.47	0.07	0.54	0.85	4.38	0.36
Jharkhand	0.15	0.00	0.15	0.24	117.92	3.02
Karnataka	7.76	1.27	9.03	14.19	64.79	5.85
Kerala	0.9	0.12	1.02	1.60	42.59	1.54
Madhya Pradesh	5.57	0.83	6.40	10.06	104.11	5.60
Maharashtra	8.99	1.41	10.40	16.34	104.38	7.48
Manipur	0.14	0.02	0.16	0.25	8.13	0.28
Meghalaya	0.05	0.00	0.05	0.08	6.35	0.18
Mizoram	0.02	0.00	0.02	0.03	4.26	0.11
Nagaland	0.05	0.00	0.05	0.08	10.06	0.27
Odisha	2.40	0.35	2.75	4.32	404.64	11.40
Pondicherry	0.10	0.02	0.12	0.19	1.72	0.10
Punjab	9.50	1.59	11.09	17.43	51.80	6.49
Rajasthan	5.17	0.81	5.98	9.40	2.00	2.85
Sikkim	0.02	0.00	0.02	0.03	2.62	0.08
Tamil Nadu	4.77	0.79	5.56	8.74	137.16	6.03
Tripura	0.09	0.01	0.10	0.16	14.20	0.40
Uttar Pradesh	17.96	3.02	20.98	32.97	492.28	22.13
Uttarakhand	0.20	0.03	0.23	0.36	1.10	0.13
West Bengal	5.17	0.93	6.10	9.59	546.07	16.51
All-India	98.27	16.18	114.46	179.87	3483.26	140.68

Table 4. State-wise emissions of non-CO₂ gases from crop residue burning for the year 2000

States	Total biomass burnt (Gg)	CH ₄ (Gg)	N ₂ O (Gg)
Andhra Pradesh	4130	11.15	0.289
Arunanchal pradesh	36	0.10	0.003
Assam	964	2.60	0.067
Bihar	3217	8.69	0.225
Chhattisgrah	410	1.12	0.029
Goa	30	0.08	0.002
Gujarat	1510	4.08	0.106
Haryana	7886	21.29	0.552
Himachal Pradesh	339	0.92	0.024
Jammu & Kashmir	659	1.78	0.046
Jharkhand	614	1.66	0.043
Karnataka	7066	19.08	0.495
Kerala	151	0.41	0.011
Madhya Pradesh	1307	3.53	0.091
Maharashtra	4721	12.75	0.330
Manipur	69	0.19	0.005
Meghalaya	48	0.13	0.003
Mizoram	21	0.06	0.001
Nagaland	54	0.15	0.004
Odisha	919	2.48	0.064
Punjab	18507	49.97	1.296
Rajasthan	1462	3.95	0.102
Sikkim	13	0.03	0.001
Tamil Nadu	3578	9.66	0.250
Tripura	97	0.26	0.007
Uttar Pradesh	19955	53.88	1.397
Uttarakhand	588	1.59	0.041
West Bengal	4337	11.71	0.304
A & N Islands	5	0.01	0.000
D & N Haveli	4	0.01	0.000
Delhi	15	0.04	0.001
Daman & Diu	1	0.00	0.000
Pondicherry	25	0.07	0.002
All-India	82736	223.39	5.792

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Life Cycle Assessment: A Case Study of Rice Production System

T Aggarwal, H Pathak and N Jain

Introduction

Life cycle assessment (LCA) is a tool for evaluating environmental effects such as emission of greenhouse gases (GHGs) from a product, process or activity throughout its life-cycle or lifetime. The LCA can be partial assessment, i.e. 'from cradle to gate' or full assessment, i.e., 'from cradle to grave'. The 'cradle-to-grave' assessment begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth, whereas 'cradle to gate' assessment is only up to factory, before going to consumer. The LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next (Roy *et al.*, 2009). The LCA is supposed to give valuable information about impacts of any production process on the environment and their possible reduction (Breiling *et al.*, 1999). It is a powerful tool which can assist in formulating environmental legislations, help manufacturers to analyze their process and enable consumers to make more informed choices. The most common categories of assessed damages in the LCA are global warming, acidification, eutrophication and toxicological products. In recent years, the LCA has been applied in the areas of agriculture and food production with the aim to improve the environmental efficiency of the production chains (Gillani *et al.*, 2010).

According to the International Organization of Standardization (ISO), the LCA is divided into four phases: goal and scope definition, inventory analysis, life-cycle impact assessment and interpretation (ISO14040, 2006).

- (1) Goal and scope definition:** This step defines the purpose, expected product, system boundaries, functional unit and assumptions of the study. For LCA studies in the agricultural sector, this could be for instance, to investigate the

environmental impacts of emissions in crop production or to analyze the advantages and disadvantages of different farming systems (Gillani *et al.*, 2010). System boundaries are generally presented in the form of an input and output flow diagram. All operations that contribute to the life-cycle of a product, process, or activity fall within the system boundaries. But a person doing LCA has the liberty to define the system boundary depending upon the availability of datasets.

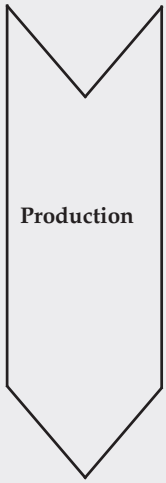
- (2) **Inventory analysis:** This phase quantifies the use of resources and energy as well as the environmental releases associated with the system being evaluated.
- (3) **Impact assessment:** It is a quantitative process to identify, characterize and assess the potential environmental impacts of any process/steps identified in the inventory analysis.
- (4) **Interpretation:** In this step, results of other steps are interpreted according to the goal of study. The outcome of this step is a set of conclusions and recommendations.

Life-Cycle Assessment of Greenhouse Gas Emission from Rice Production System

India has the largest area under rice (about 44 M ha) in the world and ranks second in the production, after China. It is a primary foodgrain crop of India and occupies about 37% of the cultivated area. Rice production is a major contributor to GHGs emission from the crop production sector. Therefore, it is important to evaluate the life-cycle of rice and rice products to determine an energy-effective rice production and consumption pattern to reduce GHGs emission. A simplified methodology of LCA of GHGs emission from rice production system, developed by Pathak *et al.* (2012), is explained below.

Various components and stages of the life-cycle of rice production system that are associated with GHGs emission are shown in Figure 1. All stages of production including tillage, inter-culture and harvesting and activities related to post-harvest storage and processing prior to its entry into the trading system for sales to final consumers are identified. In addition, the indirect contribution to GHGs emission by fertilizer and pesticide manufacturing is also considered.

- (1) **Cultivation:** Conventionally, the fields are typically ploughed before seeding/transplanting of rice, the plough being drawn by a diesel-powered tractor or bullocks. In rice fields, seeding is done by either direct seeding or seedling

Stages	Process	Equipment	Input	GHG
 Production	Tillage	{ Tractor/Power tiller Bullock	Diesel -	CO ₂ CH ₄ /N ₂ O
	Sowing	{ Seed drill Manual	Diesel -	CO ₂ -
	Transplanting	Manual	-	-
	Irrigation	Pump	Diesel/electricity	CO ₂
	Fertilizer production	Factory	Electricity	CO ₂
	Fertilizer application	{ Fertilizer drill Manual	Diesel -	CO ₂ -
	Biocide production	Factory	Electricity	CO ₂
	Biocide application	Sprayer	-	-
	Soil microbial processes	-	-	CH ₄ /N ₂ O/CO ₂
	Harvesting	{ Combine Manual	Diesel -	CO ₂ -
 Processing	Drying	{ Sun drying Machine dryer	- Electricity	 CO ₂
	Milling (parboiling)	{ Stove Rice mill	Biomass Electricity	CO ₂ CO ₂
	Packaging	Bag	Electricity	CO ₂
 Marketing	Transporting	Truck/Rail	Diesel/electricity	CO ₂
	Storing	Warehouse	Electricity	CO ₂
 Consumption	Cooking	Oven	Gas/electricity	CO ₂

Source: Pathak *et al.* (2012)

Figure 1. Schematic presentation of different steps and processes associated with greenhouse gas emission in the life cycle of rice

transplantation by hands. After seeding/transplanting, irrigation is given using a diesel/electricity-powered pump. Diesel consumption by tractors contributes to CO₂ emissions. The field is flooded with water which leads to anaerobic conditions and consequently methane, a GHG, is produced. Nitrogenous fertilizers, applied 3-4 times depending upon soil fertility, variety and yield target lead to the emission of nitrous oxide, another GHG.

- (2) **Harvesting and post-harvest activities:** After maturity, the crop is harvested by either combine harvesters or manually which is followed by threshing.

After harvesting and threshing, rice is dried to reduce its moisture content up to 14%. Drying is done either in the shade or by means of mechanical drier. Remaining impurities like pieces of stones, dust, lumps of mud are removed by winnowing. After cleaning, parboiling is done in some places such as in eastern and southern India by soaking rice in water for a short time, followed by heating once or twice in steam and drying before milling. Milling is done to remove the husk and retain a specified percentage of bran from the seeds. Rice husk, a by-product of milling industry, is used for generating steam for parboiling paddy and as heat source for mechanical dryers.

- (3) Marketing and packaging:** Rice is transported usually in bulk from field to the market. The average transport distance varies from 100 km to 1000 km in different parts of the country. Packaging of food is the vital step to ensure longer shelf-life and preservation of quality of the product and provide protection against deterioration and damage during transport and storage. The Government of India has made it obligatory to pack entire foodgrains in jute bags only. The bags are transported by means of bullock carts, tractor trolley, trucks and railways.

Emissions of the GHGs emitted during each of the above discussed processes are calculated using data directly measured or obtained from literature. In rice production system maximum GHGs emission is associated with the cultivation process followed by marketing and parboiling.

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Section III

Impacts of Climate Change on Agriculture

Impact of Elevated Carbon Dioxide Concentration on Crop and Soil

SD Singh, B Chakrabarti, S Naresh Kumar and H Pathak

Introduction

Increasing atmospheric carbon dioxide concentration and simultaneous rises in temperature are influencing the global climate, henceforth affecting growth, development and functioning of plants. The primary effects of increased concentration of CO₂ include higher photosynthetic rate, increased light-use efficiency, reduction in transpiration and stomatal conductance and improved water-use efficiency (Drake *et al.*, 1997). Most of the studies on impact of elevated CO₂ on crop species, reported earlier, have been based on controlled environment or enclosures (Norby *et al.*, 1999; Wand *et al.*, 1999) like green houses, controlled environmental chambers, open top chambers, and other enclosures to confine CO₂ gas around the experimental plants. However, concerns have been expressed that the results obtained from such enclosure-based CO₂ enrichment systems might not be the true representatives of the open field conditions.

Free-air carbon dioxide enrichment (FACE) experiments are conducted to study the effects of elevated CO₂ on plants grown under natural conditions without enclosure (Ainsworth and Long, 2005). In India, the impact of elevated CO₂ on rice crop grown inside a FACE ring was studied by Uprety *et al.* (2003). The most sophisticated FACE system was designed by Brookhaven National Laboratory's FACE Group, which employed computer regulation of CO₂ concentration in the FACE rings (Miglietta *et al.*, 1997). The FACE system has been utilized with some variations and technical modifications in several experiments including studies on cotton, wheat, grassland and desert ecosystems, forest and plantation trees (Table 1) (Long *et al.*, 2004).

Table 1. FACE experiments conducted at different locations on various crops

Location	Vegetation	Year	CO ₂ (ppm)	Ring diameter (m)
University of Arizona, USA	Cotton	1989-91	550	25
	Wheat	1993-94	550	25
	Sorghum	1999-00	Ambient + 200	25
Rapolano, Terme, Italy	Potato	1998-99	560	8
Cedar Creek, Bethel, USA	Tall grass prairie	1997-2001	550	23
University of Illinois, USA	Soybean	2001-02	550	20
	Corn	2002	550	20

Source: Adopted from Long *et al.* (2004)

Free-Air CO₂ Enrichment (FACE) System

Description of FACE system

A typical FACE system comprises an approximately circular facility and is surrounded by an array of vertical or horizontal pipes that release CO₂ or air enriched with CO₂ at vertical intervals from just above the ground to vicinity of the plant canopy (Fig. 1). The FACE ring (plenum) is made up of eight horizontal PVC pipes. These pipes located on the perimeter of an octagon are placed on the height-adjustable stands. This system allows releasing CO₂ near the canopy for crops of varying heights. At one end of each arm of the plenum is fitted to

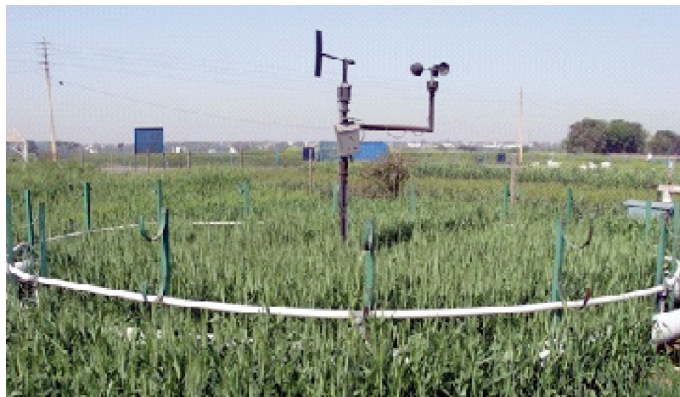


Figure 1. Free-air CO₂ enrichment (FACE) facility at IARI, New Delhi

centrifugal air blower to allow circulation of a large volume of air and the other end is closed. Each arm of the plenum has an independent CO₂ injection system and CO₂-mixed air is released through the small holes on the pipe near the crop canopy. Each pipe is connected to a solenoid valve which is used to release CO₂-enriched air into the ring. Opening and closing of the solenoid valves in the rings are regulated by the speed and direction of wind. Wind speed and direction are measured at a height of 8 feet in the same plane by a sensitive cup anemometer and wind vane. CO₂ is released from the pipes present in the upwind direction at any given time.

Carbon dioxide is supplied through pipes from CO₂ cylinders. Five cylinders are connected to a manifold system which releases CO₂ to the compressor. From the cylinders, CO₂ is released through a manifold system which is connected to a pressure gauge regulator and a flow meter. Each FACE ring has temperature and humidity transmitters with weather shielding along with one suction line at the centre. The sensors record the ambient air temperature and humidity at regular intervals.

Air sample is sucked from 3 points through pipe. Infra-red gas analyzer (IRGA) measures CO₂ concentration in the air and it is logged in the computer. The computer is connected to an indigenously developed control system the FACEMATIC control system (Neo-Genesis Engineering, India) and Supervisory Control Data Acquisition (SCADA) software (Fig. 2). The CO₂ concentration data is passed from the computer to the FACEMATIC system. This system regulates CO₂ release and maintains its desired level inside the rings. If CO₂ concentration inside the FACE ring is less than the set value, the FACEMATIC actuates opening of the 3 solenoid valves located upwind of the FACE plot as a function of the most frequent wind direction. The CO₂ concentration measured by IRGA is logged automatically in the computer at every 5-minute interval. Data on temperature, relative humidity, wind speed and direction are also logged in the computer.

Designing of Experiment

The field experiment on the selected crop is conducted in the FACE ring and also in the open field as control. The area inside a FACE ring is divided into four parts, each part representing one replication. The system is run for at least 8 to 10 hours daily during the daytime to expose the crops to high CO₂ condition. The desired CO₂ level is set in the computer to allow the system to maintain this level



Figure 2. A frontal view of FACEMATIC and SCADA system

inside the ring. As the crop grows, height of the ring is adjusted in order to supply CO_2 at the canopy level of the crop. Similar crop management practices like seed rate, spacing, irrigation, fertilizer and manure application, etc. are followed in both FACE and control plots. During crop growth period, various observations like crop phenology, photosynthesis rate, transpiration, leaf area index, leaf chlorophyll content, biomass, grain yield, etc. are recorded from the FACE ring as well as from control plots. Besides crop growth parameters, soil parameters like soil moisture content, soil nutrient status, etc. as well as green house gas (GHG) emission are also recorded from FACE and control plots.

Interpretation of Data

Data of elevated- CO_2 logged in the computer is downloaded and mean elevated CO_2 level during the crop growth period is calculated. From this data, short (hourly), medium (daily) and long-term (monthly) fluctuations in CO_2 concentration inside the ring can also be worked out. Plant and soil parameters recorded inside the FACE ring as well as in the control plot are compared. This helps in assessing the impact of elevated- CO_2 on crop growth parameters and soil properties.

Maintenance of FACE System

IRGA is regularly calibrated every 7 days at zero CO_2 level using pure nitrogen (N_2) gas and once in a month with the known concentration of CO_2 . During commissioning, CO_2 concentration in the FACE ring is measured at different

locations using portable CO₂ analyzer and CO₂ flow rate is adjusted till CO₂ concentration in the entire FACE ring is <10% of the target concentration.

Expenses Involved in FACE System

A FACE system involves both capital and operating expenses. The cost of installing a FACE ring was US\$ 50,000. The operating cost of the system included expenses on CO₂ and electricity and the maintenance cost included cost of N₂ cylinder for calibration, silica gel, and cost of labour. Electricity was required for running the compressor, pump, air blower, IRGA, PC and the air-conditioning system of the control room. A comparison of IARI FACE system with other FACE experiments showed that the annual operating cost per unit area for this setup in India was less than the similar setups in USA, Italy and Switzerland. It would be attributed to lower cost of CO₂, electricity and maintenance in the FACE setup in our country.

Performance of IARI FACE System

The FACE system in IARI is able to maintain the desired CO₂-level inside the ring. It is run daily for 10 hours (8 a.m. to 6 p.m.) during the cropping season. The monthly mean values (long-term) of CO₂ concentration inside the rings during 10-hourly period of its operation indicated that the desired CO₂-level (550 ppm) was maintained inside the ring from July to April, 2007. Mean values of CO₂ concentration during this period ranged from 525 ppm to 553 ppm (Fig. 3). Distribution of CO₂ concentration inside the ring showed variation of 8-10% from periphery to the centre of the ring, suggesting spatial uniformity of CO₂-level inside the ring.

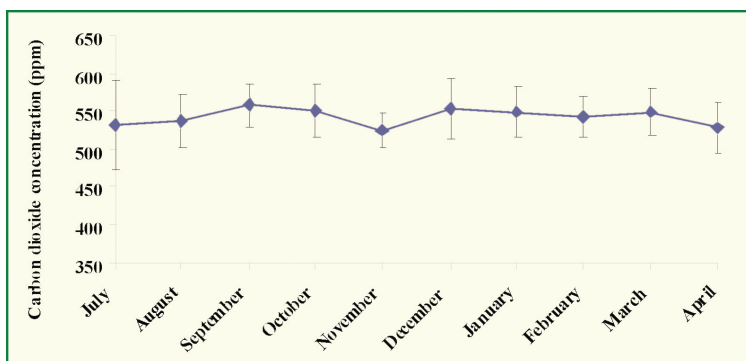


Figure 3. Monthly average CO₂ concentrations inside a FACE ring

Open Top Chamber (OTC)

Open Top Chamber (OTC) is another prevailing approach for studying the impact of elevated- CO_2 on crop production. Earlier during 1990s, studies on the impact of elevated- CO_2 on crops grown inside OTCs were initiated at the Indian Agricultural Research Institute (IARI), New Delhi (Uprety, 1998). OTCs consist of metal construction with transparent vertical side-walls made up of polyvinyl chloride (PVC) sheet (Fig. 4). Top of the structure is kept open to allow the natural air exchange and maintain normal temperature and humidity. CO_2 -enriched air is distributed inside with the help of circular tubes fitted at the base of OTC. Pure CO_2 is supplied from cylinders containing 100% CO_2 of commercial grade. One such facility of OTC has been developed at the Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad for continuous monitoring and maintaining the desired CO_2 level, temperature and relative humidity (Vanaja *et al.*, 2006). CO_2 was supplied to the OTCs and maintained at set levels using manifold gas regulators, pressure pipelines, solenoid valves, rotameters, sampler, pump, CO_2 analyzer, PC linked programme logic control (PLC) and supervisory control and data acquisition (SCADA). Air inside the OTC is drawn by pump and air sample is analyzed with the help of Infra Red Gas Analyzer (IRGA). If CO_2 concentration is below the set value, then solenoid valves open and CO_2 is released. This helps in maintaining the desired CO_2 level inside the OTC.



Figure 4. Open top chambers (OTC) in IARI field, New Delhi

Advantages of FACE System

FACE studies are completely open air and have many benefits over controlled environment and open-top chamber (OTC) experiments. FACE allows the investigation of an undisturbed ecosystem and does not modify the vegetation's interaction with light, temperature, wind, precipitation, pathogens and insects.

This, in combination with the large size of FACE plots, allows the integrated measurement of many plant and ecosystem processes simultaneously in the same plot, avoids many of the problems associated with edge effects prevalent in OTCs, enables significantly more plant material to be harvested without compromising the experiment, and allows plants to be studied throughout their life-cycle, including trees that have enough space to develop to canopy closure. Many studies using elevated CO₂ have been conducted in enclosed areas, such as growth chambers, OTCs and greenhouses, where it is relatively easy to control the levels of CO₂. But within these enclosures it is difficult to study plants under certain natural conditions, such as temperature, pollination, wind, humidity, and sunlight. Size of the plant growth and experimental area are also constrained when using these technologies. The bigger size of FACE helps in reducing the edge effect and conducting on the studies under open field conditions.

The FACE system uses the natural wind conditions to carry CO₂-enriched air across the vegetation. Since plants are in the natural environment, the chamber effects normally created by enclosures are reduced or eliminated. In OTCs relative responses are obtained, while the FACE provides the absolute responses. The sheets used to make the side walls of an OTC decrease the transmittance of solar radiation to a certain extent. According to Geider *et al.* (2001), the OTCs in forests can accommodate only one or two moderately-sized trees and edge effects are likely to be extreme. Under such conditions, FACE could be a viable alternative and is considered a consolidated technique to expose crops, forest plantations and natural vegetation to the conditions of elevated atmospheric CO₂ concentrations that are expected to occur in the near future.

A Case Study

During 2007-09, an experiment was conducted at IARI farm on four crops (green gram, soybean chickpea and wheat) inside the FACE ring (Singh *et al.*, 2010). It was found that biomass as well as grain yield increased in all these crops under

Table 2. Effect of elevated CO₂ level on yield of selected crops

Parameters	Ambient CO ₂ level (380 ppm)	Elevated CO ₂ level (550 ppm)	CO ₂ fertilization effect (%)
Greengram			
Biological yield (g m ⁻²)	270	295	9
Seed yield (g m ⁻²)	92	102	11
Soybean			
Biological yield (g m ⁻²)	463	530	14
Seed yield (g m ⁻²)	190	220	16
Chickpea			
Biological yield (g m ⁻²)	694	800	15
Seed yield (g m ⁻²)	213	258	21
Wheat			
Biological yield (g m ⁻²)	1068	1260	18
Seed yield (g m ⁻²)	442	516	17

Source: Adopted from Singh *et al.* (2010)

the elevated CO₂ condition (550 ppm) (Table 2). The enhancement in yield was associated with increase in the number of pods/plant, number of seeds/pod, number of spikes/m², number of grains/spike, etc.

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Impact of High Temperature on Crop and Soil

B Chakrabarti, SD Singh, A Anand, Madan Pal Singh
H Pathak and S Nagarajan

Introduction

The global temperature has increased by 0.74 °C during the past 100 years. The recent report of IPCC (2007) has reconfirmed the increasingly strong evidence of global climate change and has projected that the average atmospheric temperature across the world would rise by 1.8-4.0 °C by the end of the twenty-first century, depending upon the adoption of developmental pathways by countries. Increasing temperatures and carbon dioxide levels in the atmosphere along with the uncertainties in annual precipitations will have adverse effects on the Indian agriculture. Biomass and yield tend to decline with increasing temperature, as higher temperatures shorten crop duration, enhance respiration and reduce time for radiation interception (Rawson, 1995). As yields in some of the most productive regions of the world are approaching a plateau or even declining (Pathak *et al.*, 2003), the likely effect of climate change on crop production adds to the already complex problem. It is a major challenge to evaluate the impact of rising temperature on crop yield. Various technologies have been adopted to study the impact of high temperature on crop growth. Portable/ movable chambers as well as walk-in tunnels are used to raise crops under conditions of high temperature. The advent of the temperature gradient tunnel (TGT) (Mihara, 1971; Okada *et al.*, 1992; Nakagawa *et al.*, 1993; Rawson *et al.*, 1995) has enabled the researchers to find responses of crops in the field to a range of temperatures within the same chamber. The gradient system offers the advantage of a wide range of temperature combinations in fields which are realistic in terms of farming practices.

Temperature Gradient Tunnel (TGT)

Description of TGT System

Temperature gradient tunnels offer a novel methodology to study a large number of plants grown under a range of temperatures. It consists of a series of semicircular bows anchored in the soil. The bows are covered with polycarbonate sheet or UV stabilized polythene sheet to create a greenhouse like atmosphere, having a temperature higher than the outside environment (Fig. 1). The sheet is clear with 90% transparency level. Air inside the tunnel is heated naturally by the incident solar radiation during the daytime. Thermal gradient is created by sucking ambient air into the tunnel from one end (inlet) and releasing it from the other end (outlet). The fan speed is regulated to get the desired level of temperature gradient. Temperature sensors are installed inside the tunnel at regular intervals to measure air temperature at different points of the tunnel and data are recorded by data logger. A humidity sensor is used to measure the humidity inside the tunnel. The TGT is connected to a computer system wherein temperature data is logged at regular intervals (one-minute) throughout the cropping season. The system remains operational for 24 hours (day and night) throughout the crop growing period and temperature gradient data are recorded during this period.



Figure 1. Temperature gradient tunnel (TGT) at IARI, New Delhi

Designing of Experiment

The area inside the tunnel is divided into the number of plots equal to the number of temperature sensors installed inside the TGT. Crops are sown in those plots

following similar management practices. The plot area is divided into 5 sectors and sensors are placed in these 5 sectors. Since temperature gradient exists inside the tunnel, these crops are automatically exposed to varying temperatures. During the crop growth period, different parameters, like crop phenology (days to anthesis, days to maturity), crop physiological processes (photosynthesis rate, transpiration rate, pollen sterility), biomass and grain yield of crop are recorded from each plot. This allows a comparison of the growth of crop grown at different temperatures. Besides crop, soil parameters are also recorded. Soil thermometers are installed in each plot to record changes in soil temperature at different parts of the TGT. Soil moisture content, nutrient status, etc. are also measured to study the effect of increased temperature on soil properties. Observations recorded on soil parameters are useful for correlating crop yield with temperature rise at the end of the experiment.

Interpretation of Results

At the end of the season, temperature data is downloaded from the system. The data provides temperature of 5 sensors installed inside the TGT at one-minute interval. From this data daily and then monthly or seasonal mean temperature values can be calculated. Besides this, the temperature data of the sensor installed outside the TGT gives the ambient temperature of the cropping season. These values are used to quantify the difference in temperature in different sections inside the TGT as well as temperature difference inside and outside atmosphere. Thus, seasonal temperature gradient is calculated for the entire TGT. Afterwards, these temperature values are correlated with various parameters of crop growth, yield and soil properties. A positive correlation indicates a positive effect of temperature on crop and soil processes and vice versa. This helps in assessing the impact of elevated temperatures on crop growth, productivity and soil health.

Maintenance of TGT

In order to maintain high transparency the sheet is cleaned frequently, depending on the dust deposition load on the sheet. Temperature sensors are calibrated regularly to get actual values of temperature inside the tunnel. The tunnel door is kept closed for most of the time to maintain appropriate temperature gradient.

Portable Field Enclosures/Tunnels

Field chambers of various designs have been used extensively in determining the impact of high temperature on phenology and yield of crops. These chambers are movable structures that can be used to cover the crop at different developmental stages in the field. These polycovers/acrylic chambers have been useful in many ways in horticultural crops production besides being utilized in elevated temperature studies (Fig. 2). The temperature rises in these polycovers due to natural trapping of heat of sunrays during the daytime and retaining of this heat within the plastic cover at night. In the field experiments on the short-period effects of high temperature during pre- and post-anthesis in wheat, the crop was exposed to different temperatures by covering the reproductive part (spike in the case of wheat) with acrylic rectangular boxes (Calderini *et al.*, 1999). These boxes having dimensions of 50 cm × 20 cm × 6.5 cm with an open base were supported at the southern end by a wooden stake. Mean high temperatures of 2.6 °C to 4.2 °C could be achieved with this setup.



Figure 2. PVC enclosures in a field crop

Portable Field Temperature Gradient

The portable field temperature gradient can be achieved by the technique followed by Gutierrez *et al.* (2009) in their CO₂ and temperature related studies in wheat. They used the chambers which were 9 m long, 2.2 m wide and 1.7 m high at the

ridge. The walls of the chamber were made of polycarbonate and the roof was of polyethylene sheet. These chambers were mounted over the crop standing in the field. These chambers did not have heating system and used passive ventilation for air exchange and cooling. Rolling up of the sides or opening of door at both the ends provided the cooling effect. The chamber consisted of three modules (of 3 m length) each separated by a septum made of polycarbonate to reduce the mixing of air between the modules. Inlet fans and outlet fans and heaters kept the inlet module at a temperature close to outside atmospheric temperature and the final outlet module was at 2 °C higher temperature. The middle module acted as a spacer. The chambers were kept at ambient/ elevated during the night hours.

Walk-in Tunnel

A walk-in tunnel is a greenhouse like structure without any electrically powered heating or ventilation system, covered with one layer of plastic and sited on field soil (Wells and Loy, 1993). Waldo *et al.* (1998) used such walk-in tunnels for growing muskmelons. The tunnel was 18.3 m long, 8.2 m wide at the base and was 3.3 m high at the apex. It was covered with 0.152 mm polyethylene, film which was condensation-resistant, UV-resistant and infra-red barrier and ran from ground to ground. Thermocouples measuring air temperatures were protected from direct solar radiation by shade structures. It is vital to maintain adequate ventilation in the tunnel. Sidewall openings or roof vents increase ventilation capabilities of the tunnel. The tunnels also had thermal tubes lying beside each raised bed. Thermal tubes are polyethylene tubes filled with water and laid alongside crop rows. The water in tubes absorbs solar energy during the day and releases it during the night. Tunnels with thermal tubes could maintain 1-2 °C higher night temperature than other tunnels.

Free Air Temperature Increase

A technique called Free Air Temperature Increase (FATI) is also available to artificially induce increased temperatures under field conditions. Warming is simulated in the experimental plots by heating the canopy with an irradiation unit placed 1-2 m above the ground, supplying infrared radiation at an angle of 40° above the horizontal field (Nijs *et al.*, 1996). This allows irradiation also during the night (the plants are heated but in the dark). Each irradiated plot is paired with a reference plot, in which a 'dummy' irradiation unit without lamps is used.

Recently, a new technique called Free Air Temperature Enrichment (FATE) has been developed to artificially induce canopy temperature in open field conditions without the use of enclosures. The FATE system simulates warming in small ecosystem of limited height with thermal radiation and canopy temperature across the plot. This new technology is based on a series of micro-computer systems for effective control of temperature and CO₂ concentration needs to be developed.

A Case Study

A temperature gradient tunnel (TGT) installed at IARI farm was used to assess the impact of high temperature on crop growth and yield during *rabi* season of 2008-09. It was found that TGTs were able to maintain the temperature gradient in wheat and chickpea crops (Fig. 3). The study revealed that high temperature reduced the duration of crop growth in both wheat and chickpea. The period for 50% flowering in wheat and chickpea crops was decreased by 5 days with 2.9 °C and by 6 days with 3.1 °C rise in temperature. Rise in temperature inside the TGTs also led to reduction in biomass and grain yield of both wheat and chickpea crop (Table 1).

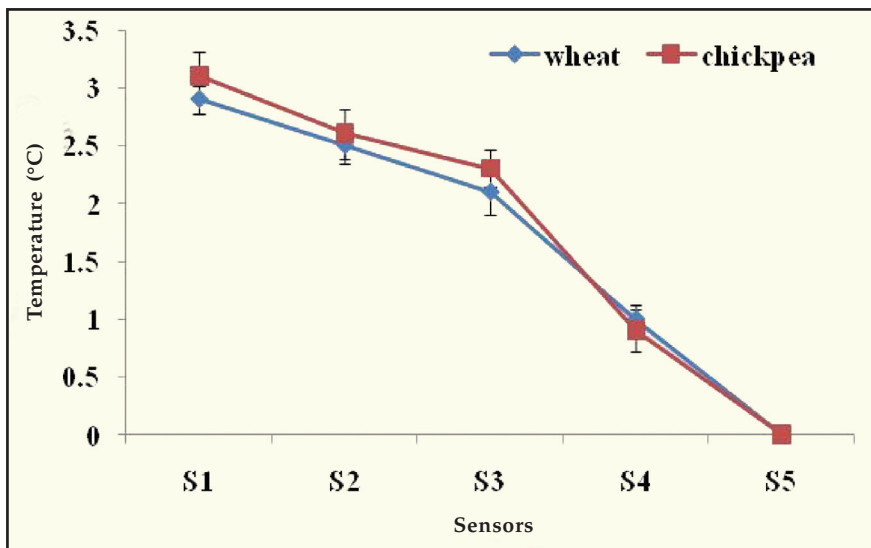


Figure 3. Temperature gradient inside the TGTs growing wheat and chickpea crop

Table 1: Effect of high temperature on yield of wheat and chickpea crops

Temp. gradient (°C)	Biological yield (g m ⁻²)	Grain / seed yield (g m ⁻²)
Wheat		
0	1216	368
+1.0	1060	320
+2.1	1000	295
+2.5	914	280
+2.9	798	251
Chickpea		
0	773	228
+0.9	722	197
+2.3	695	195
+2.6	638	192
+3.1	606	190

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Quantification of Climate Change Impacts on Crops: Field Experimentation

A Anand, Madan Pal Singh and S Nagarajan

Introduction

Global surface temperatures are projected to increase because of radiative and physiological effects of the changes in environment. This would lead to vital changes in crop production in agriculture in future, as it will be coupled with increased concentration of carbon dioxide in the atmosphere. The impact of these climatic changes on crop yields has been evaluated by growth chamber or indirect methods using simulation models. However, direct studies on the impact of observed climate change on crop growth and yield could provide more accurate and realistic information that can be used for assessing the effect of climate change on crop production. But, it is not easy to conduct large-scale field experiments to assess the effect of change in temperature or CO₂ concentration on crop growth and yield. There are three approaches to this study, each having its merits and demerits. We shall discuss them one by one in this chapter.

Field Experiments

(a) Multi-location Trials

Among various approaches used to study the response of crop species to rising temperature, field experiments conducted at different locations under natural environment are more realistic. This approach may be used to study the response of crop plants to a range of temperature, starting from the optimal to detrimental levels. The locations may be selected based on the levels of temperature at different altitudes, as the temperature will be higher with a decrease in altitude. The study requires continuous monitoring of all the climatic factors like maximum and minimum temperatures, humidity, level of radiation and rainfall every day during the crop season at each location. For measuring these parameters, we need to fix

specific sensors and data loggers attached with microprocessor at every experimental site. This approach may be used to study the response of few genotypes to different levels of temperature as well as screening of a large number of genotypes. But, this approach has some limitations like the soil characteristics and photoperiodic conditions for each location may vary. Therefore, it is necessary to take into account, data on changes in these two factors before analysis of data. Various studies have been conducted worldwide for studying high temperature response of different crop species using the above approach (Muchow *et al.*, 1990; Stewart and Dwyer, 1998; Redfearn *et al.*, 2005; Lobell and Field, 2007; Silim *et al.*, 2007). The study conducted by Silim *et al.*, (2007) in Kenya to find the response of pigeonpea genotypes to temperature is discussed below as a case study.

Case Study

Six genotypes representing different maturity durations were selected and grown at five different locations in Kenya. Day length was increased using 100 W incandescent bulbs suspended 2.0 m above ground and 1.5 m apart. These bulbs were connected through an automatic switch to turn them on and off during early morning and late evening hours. The latitude of the experimental sites ranged between 4°25' and 1°15' S.

- (a) *Data collection*: During duration of the experiment, data were collected on daily maximum and minimum temperatures, time to flowering, rainfall and photoperiod. The soil types were also recorded for each site of the experiment. Data collected for each site in this study has been indicated in Table 1.

Table 1. Temperature, rainfall and soil type at the experimental sites in Kenya

Location	Latitude (South)	Altitude (m)	Soil type	Temperature (°C)			Rainfall (mm)
				Max.	Min.	Mean	
Niwapa	4°25'	50	Deep sandy Clay loam	31.4	23.2	27.3	370
Kiboka	2°20'	900	Sandy clay, Loam, calcareous	29.4	17.7	23.0	464
Katumani	1°35'	1560	Very deep sandy loam to clay	25.6	14.4	20.0	467
Kabete	1°15'	1825	Extremely deep friable clay	24.6	12.9	18.7	478
Muguga	1°15'	2095	Extremely deep friable clay	22.0	11.5	16.8	462

Source: Silim *et al.* (2007)

The mean pre-flowering maximum and minimum temperatures for each genotype were calculated using daily temperature values from sowing until 50% of plants in a plot had at least one open flower. Time to flowering was recorded for each genotype. The mean pre-flowering photoperiods for each genotype were calculated using daily photoperiod between sowing and flowering. The response to temperature and photoperiod from sowing to flowering (f) was based on means of three replications for each genotype-environment. Rates of progress from sowing to flowering were calculated as $1/f$ (reciprocal of the time from sowing to flowering) for each genotype using the protocol developed by Summerfield *et al.* (1991). This protocol is based on three well-defined relations between $1/f$ and mean pre-flowering temperature (T) and mean pre-flowering (P).

(b) Staggered sowings

A simple approach to quantify the effect of temperature on a crop in the field is to sow the crop on different dates, thereby testing across the large seasonal changes in temperature for different thermal regimes. This method of creating different environments to study the impact of climatic factors is widely used. Either a large number of sowings are done in the same crop season at short intervals (Saini and Dadwal, 1986; Nagarajan *et al.*, 2010), or four to six sowings are done in three or more consecutive years (Krishnan and Rao, 2005). Though it removes the variability in soil types which are encountered in multi-location experiments, it has an inherent problem of varying photoperiod and light intensity (radiation) which affect the phenology of the crop. These effects depend on the location and the crop that is being studied. In tropical regions, day length does not change much during the experimentation period, whereas in sub-tropical regions, day length changes significantly during the crop season. Similarly, some crops and varieties are light-sensitive and others are light-insensitive. All these factors have to be considered while doing an experiment with staggered sowing.

Case Study

Field experiments and lab analyses were conducted in 2005, with five high-yielding rice varieties including aromatic and non-aromatic types, exposed to twelve different diurnal temperature (day/night) and radiation regimes to ascertain the impact of diurnal temperature and radiation changes on yield and yield components of aromatic and non-aromatic rice varieties in the field conditions and to document their effect on the grain and seed quality.

Methodology

The field work was carried out at the experimental farm, Division of Genetics, Indian Agricultural Research Institute (IARI), New Delhi, India during 2005. Five rice cultivars, three Basmati rice cultivars (Pusa Sugandh-2, Pusa 1121 and Super Basmati) and two non-Basmati cultivars (IR-64 and Pusa-44) were selected for this study. Among these varieties, Pusa 1121 and Super Basmati were photosensitive, while the remaining three varieties were photo-insensitive.

Field Preparation and Crop Management

Field preparation and crop management were followed according to the standard practices for this region. Certified seeds of all the five rice cultivars were sown on 12 different dates and 30 days old seedlings were transplanted. Accordingly, one seedling/hill was transplanted on 12 different dates separated by weekly intervals with the first transplanting starting in the first week of June and the last in the fourth week of August 2005. Randomized Block Design (RBD) was followed and 12 naturally different growing environments (E) were created. Each experimental plot was 1.26 m² and seedlings were transplanted at a spacing of 20 cm × 15 cm with 7 rows of 1.2 m length accommodating 42 plants per plot. Three replicate plots of similar dimensions were maintained for each genotype and for each independent transplanting. Nitrogen in the form of urea was applied @ 60 kg ha⁻¹ in 3 equal splits at (i) basal (at the time of transplanting), (ii) active tillering and (iii) panicle initiation stages. Phosphorus (30 kg P₂O₅ ha⁻¹) and Potassium (30 kg K₂O ha⁻¹) were applied uniformly to the puddled sandy loam soil at the time of transplanting. Weather data including daily maximum, minimum temperatures, relative humidity (RH) and mean monthly radiation for the experimental period were obtained from the IARI observatory.

Sampling and Data Collection

Five plants from each replicate were harvested randomly from the base of the hill, from the middle five rows avoiding border row effect and used for recording yield components such as biomass, panicle length, panicle weight, and spikelet fertility, grain weight per plant and harvest index. Three replicate samples of 1000 grain each were separately counted and the 1000 grain weight was recorded.

Grain Yield

The remaining 37 hills from each replicate were harvested at physiological maturity and the grain and straw separated. The grains were air dried to 10-14% moisture content and the grain yield was recorded and expressed as kg/m² after adding back the grain weight of the five plants used for measuring the above yield components.

Grain Quality

Grain quality traits like milling and hulling percentage, chalkiness of the grain, aroma in basmati varieties, amylose content, gelatinization temperature, length-breadth ratio of un-cooked grain and elongation ratio of cooked grain were recorded.

Statistical Analysis

The grain yield, yield components and vegetative parameters, were analyzed as randomized block design with 5 genotypes × 12 environments × 3 replications, using Genstat ver 8.1. The grain and seed quality data were analyzed as completely randomized design using the same statistical software. The partial correlation coefficients for (i) minimum night temperature (MNT) keeping radiation constant and (ii) radiation having a constant MNT was obtained from SAS version 9.1.

Findings

The grain yield was significantly different across genotypes, environments and genotype and environment interaction (Table 2; $P < 0.001$). The grain yield of all the five varieties was most significantly influenced by MNT ($P < 0.001$), followed by radiation ($P < 0.001$), explaining 87% and 77% of the yield variation respectively. Highest yields were recorded around a very narrow optimum temperature of 23°C to 24°C, with subsequent increase in temperature even by 1°C or 2°C, significantly reducing the grain yield. On the other hand, maximum day temperature resulted in a very poor fit either linearly or quadratically with grain yield, with >95% of the data points lying in 33-35°C, within the critical thresholds.

Similar to grain yield components, all the grain quality parameters tested were significantly affected by genotypes, environment and $G \times E$ interaction (Table

Table 2. Mean sum of squares of traits measured for five genotypes of rice under 12 different environments at IARI, New Delhi

Traits measured	Genotype (G)	Environment (E)	G × E	Residual
Yield and yield components				
Grain yield (t/ ha)	11.2***	59.5***	2.7***	0.8
Harvest index (%)	0.087***	0.045***	0.013**	0.007
Spikelet fertility (%)	969.4***	404.3***	98.0***	20.5
Grain weight/ plant	98.27**	1384.45***	102.11***	21.32
No. of seeds/panicle	42161.2***	6752.7***	1263.8***	220.3
Panicle weight (g)	23.3***	4.3***	0.7***	0.2
Panicle length (cm)	94.5***	71.6***	4.8***	1.5
1000 grain weight	1044.3***	25.8***	8.7***	4.0
No. of productive tillers	588.7***	154.5***	31.2***	10.8
Grain quality				
Aroma ⁺⁺	8.48***	1.46***	0.18	0.34
Amylose content	58.7***	24.0***	3.9***	0.49
Gelatinization temperature	27.14***	2.31***	1.28***	0.28
Grain elongation ratio	1.91***	0.17***	0.03***	0.009
Grain length/width ratio	18.8***	0.91***	0.15**	0.07
Proportion of high-density grain	0.073***	0.020***	0.007***	0.001

Note: **, *** indicate the level of significance at $P < 0.01$ and $P < 0.001$, respectively.

⁺⁺ Only for three aromatic cultivars

1; $P < 0.001$), except aroma which had no significant interaction with the environments ($P > 0.05$). The MNT had a negative effect on aroma, amylose content, but a positive effect on proportion of high density grain. Radiation, however, had a positive effect on all the three traits (Table 3). In general, a decline in grain quality was influenced by increased night temperature in comparison to yield components.

(c) Historical Yield Trials

By analysing weather data over a long period (15-20 years), the temperature trend at a particular place can be assessed and related to the crop performance

Table 3. Impact of mean minimum temperatures during grain growth on gelatinization temperature of basmati and non-basmati cultivars and aroma of basmati cultivars at IARI, New Delhi

Genotype	Temperature regimes (°C)					
	Gelatinization temperature			Aroma		
	14-18	19-21	22-26	14-18	19-21	22-26
Basmati rice						
Pusa Sugandh-2	Low	Low	Low	Medium	Medium	Low
Pusa-1121	Low	Low	Low	Medium	Low	Low
Super Basmati	Medium	Medium	Medium	High	High	Medium
Non-basmati rice						
IR-64	Medium	Medium	High			
Pusa-44	Low	Low	Low			

at that place. This approach is valid if the same variety of the crop is used over the years following same agronomic and cultural practices. If the same variety and packages of practice are not used, then corrections for yield gain due to improved variety and management in yield are to be calculated and applied.

Case Study

A classical example of such a study is the one conducted in IRRI, Philippines by Peng *et al.* (2004). They have analysed the weather data at the IRRI farm from 1979 to 2003 to examine temperature trends and the relationship between rice yield and temperature by using data from irrigated field experiments conducted at the farm from 1992 to 2003. Similar studies on wheat have been reported by Blumenthal *et al.* (1991) wherein grain quality results for variety trials extending over a period of 27 years have been compared with temperature profiles during the grain filling period.

Methodology

- *Weather Data Collection:* From a weather station nearby, daily maximum and minimum temperature, wet and dry bulb temperatures to calculate relative humidity and total radiation records are obtained for the study period.

- *Crop Data Collection:* Rice growing seasons at IRRI farm are dry (January to April) as well as wet (late June to September) season. In each growing season, IR-72 and other cultivars that varied from season to season were arranged in randomized complete block design with four replications. To eliminate genetic factors, only crop data for IR-72 were used in the study. The same levels of fertilizers recommended for dry and wet seasons were used in all the years.

Twelve hills (0.48 m^2) were sampled diagonally from a 5 m^2 harvest area for each replication at maturity to determine panicle number per hill, above-ground total biomass, harvest index and yield components.

The significance of time trends in changes of temperature and radiation was determined by testing the statistical significance of slopes at the $P < 0.05$ probability level according to Student's t-test. The relationships between yield attributes and climatic parameters were evaluated by using correlation and partial correlation analysis.

- (ii) *Analysis of Data:* Trends in maximum and minimum temperatures during the 25 year period from 1979 to 2003 showed that increase in minimum temperature (1.13°C) was 3.2 times more than that in maximum temperature (0.35°C). Mean minimum temperature increased by 1.35°C in the dry season and by 0.80°C in the wet season during 1979 to 2003 period. Mean radiation also increased during the same period.

In the dry season, maximum temperature was not related to grain yield ($P = 0.65$). There is a negative relationship between grain yield and radiation ($P < 0.01$) and a positive relationship between grain yield and radiation ($P < 0.05$). The partial correlation coefficient between grain yield and minimum temperature with radiation held constant was -0.72 and that between grain yield and radiation with minimum temperature held constant was 0.20 . This indicates that the increase in night temperature was although small in magnitude, had a negative effect on yield of irrigated rice in the dry season and that the effect was independent of radiation. In the wet season, no relationship between yield and its components with any of the weather parameters was obtained due to less year-year variability in weather parameters.

In conclusion, multi-location trials and staggered sowing have been established in most of the crops as a reliable experimental setup to study alterations in yield and grain quality in response to climate change.

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Impact of Climate Change on Soil Fertility

B Chakrabarti, N Jain, A Bhatia, SK Gupta and H Pathak

Introduction

The soil system responds to short-term events such as rainfall and also undergoes long-term changes such as physical and chemical weathering due to climate change. The potential impacts on soil health due to climate change would be in the organic matter supply, temperature regimes, hydrology and salinity. Soil carbon levels are expected to decrease due to decreased net primary production. Any gains by the increased plant water-use efficiency, due to elevated CO_2 , are likely to be outweighed by increased carbon mineralization after episodic rainfall and reduced annual and growing season rainfall. The quality of soil organic matter may also shift where the more inert components of the carbon pool prevail. The increase in soil temperature increases N mineralization but its availability may decrease due to increased gaseous losses through processes such as volatilization and denitrification.

Evaluation of Climate Change Impact on Soil Fertility

A soil can be assessed for its nutrient supplying capacity in future climate change scenarios by subjecting it to high CO_2 levels and elevated temperatures by conducting experiments in either laboratory or field. Most of the studies on the impact of elevated CO_2 levels and temperatures on soil are based on controlled environment or enclosures like greenhouses, controlled chambers and open top chambers. The most appropriate field studies for such research endeavours are free-air carbon dioxide enrichment (FACE) and temperature gradient tunnel (TGT) experiments. In free-air carbon dioxide enrichment (FACE) experiments, the effects of elevated levels of atmospheric CO_2 on plants grown under natural conditions can be measured (Ainsworth and Long, 2005). The advent of the temperature gradient tunnel (TGT) (Nakagawa *et al.*, 1993; Rawson *et al.*, 1995) has enabled researchers to study responses of crops in the field to a range of temperatures within the same chamber. This study involves four distinct phases.

Designing of Experiment

Field experiments on the selected crop are conducted in the climate change facilities (controlled chambers, OTC, FACE, and TGT) and in the open field as control. Inside a FACE or OTC system, high CO₂-level is maintained throughout the crop growth period. Carbon dioxide is supplied through pipes from the cylinders inside the FACE ring in such a way that it flows at the canopy level of the crop. In the control treatment, the crop is grown under ambient CO₂ level (380 ppm). This allows a comparison of the effect of elevated CO₂ levels on crop and soil. In the case of TGT, the crops grown inside the TGT are subjected to varying temperatures which are higher than the ambient temperature. The area inside a TGT is divided into 4 or 5 plots, and a temperature sensor is fitted in each plot to record daily temperature at regular interval. Crop is sown on these plots following similar management practices. Since temperature is the only varying factor in these plots, it becomes possible to assess the impact of increased temperatures on crop and soil.

Sample Collection

Initial soil samples are collected from all the plots prior to sowing of the crop. After the crop harvest, soil samples are again collected from control as well as CO₂ and temperature treated plots. Soil samples are sometimes collected at different crop growth stages as per the requirement of the study. Surface as well as soil samples from different depths are collected. For collection of representative soil samples, following points should be kept in mind:

- Soil samples must truly represent the study area.
- Total area should be divided into small homogeneous units.
- For soil sampling, standard sampling procedures should be followed.
- Soil samples should be collected with a *khurpi*, tube auger or screw type auger, depending on the soil type, crop grown and the soil nutrient parameters to be analyzed.
- Soil samples should be collected during daytime one hour after the climate change facility (FACE, TGT, OTC etc.) starts working.
- In FACE rings and OTC, soil samples should be collected from subplots and the area adjacent to the CO₂ release pipes should be avoided.
- From each subplot soil samples should be collected at least from 5 points.
- At each location at least 3-4 sub-samples should be collected from within 1 m area of the point and made into a composite sample.

- Soil samples should be collected from control plots growing the same crop as in the FACE ring. In the TGTs, soil samples should be collected from each plot near each sensor which is denoted by single temperature.
- Soil samples can be drawn from different depths with the help of an auger.
- Soil thermometers need to be installed in soil near every sensor to measure soil temperature of respective sub-plots inside the TGT.
- Collected soil samples should be properly labelled with treatment details and date of sampling.
- For determination of soil microbial parameters, collected samples should be immediately stored in a refrigerator maintained at 4°C for further analysis.

Analysis of Soil Samples

Collected soil samples are air dried, crushed with mortar and pestle, sieved and then used for analysis. Generally, soil is sieved through a 2-mm sieve. But for analysis of organic carbon or soil micronutrient, soil is sieved through a 0.2-0.5 mm sieve. Representative sub-samples are drawn from the collected samples and analyzed for their nutrient status following standard methodologies, as described by Jackson (1967) and Page *et al.* (1982) (Table 1). Soil parameters like soil nutrient

Table 1. Standard methods of soil analysis

Parameters	Method	Reference
Mechanical analysis	Bouyoucos hydrometer method	Bouyoucos (1962)
Water-holding capacity	Gravimetric	Piper (1966)
pH	Potentiometric	Jackson (1967)
Electrical conductivity	Conductimetric	Jackson (1967)
Cation exchange capacity	BaCl ₂	Jackson (1967)
Organic carbon	Walkley and Black	Walkley & Black (1934)
Available P	Olsen method	Olsen <i>et al.</i> (1954)
Available K	Ammonium acetate method	Hanway & Heidel (1952)
Total N	Kjeldahl	Bremner (1965)
Available N	Alkaline permanganate method	Subbiah and Asija (1956)
NH ₄ ⁺ -N	Indophenol blue method	Keeney and Nelson (1982)
NO ₃ ⁻ -N	Phenol disulphonic acid method	Ghosh <i>et al.</i> (1983)
Microbial biomass C	Fumigation extraction method	Whit <i>et al.</i> (2000)
CO ₃ ²⁻ and HCO ₃ ⁻	Titration	Richards (1954)
Ca and Mg	EDTA method	Richards (1954)
Micronutrients	DTPA-CaCl ₂ -TEA method	Lindsay and Norvell (1978)

status, soil moisture content that are likely to change with high CO₂ or elevated temperature treatment are regularly analyzed. For regular monitoring of soil temperature and soil moisture, soil thermometers as well as soil neutron moisture meter is installed inside the climate change facility for monitoring daily or hourly data.

Interpretation of Results

After analysis of the soil samples in the existing as well as changed environmental conditions, a relationship has to be established with every climatic parameter and soil parameter under study. Initial as well as final values of soil parameters will help in quantifying the impact of elevated CO₂ levels or temperatures on soil properties. Analysis of soil parameters like soil microbial biomass carbon (MBC), soil microbial biomass nitrogen (MBN), NH₄⁺ and NO₃⁻ content of soil should be carried out in between crop growth, especially after application of fertilizer or irrigation, for its better correlation with temperature, CO₂ and also greenhouse gas (GHG) emission.

Due to methodological difficulties, the below-ground system of roots, soil and associated microorganisms, often reside out of sight in such field studies. Since, the living root system is essential for the coupling of plant production to soil nutrient cycling, laboratory studies specifically set-up to mechanistically link the root-system to soil nutrient cycling should be combined with field studies.

A Case Study

To study the impact of elevated CO₂-level on soil nutrient status, a field experiment was conducted at IARI research farm on rice and wheat crops. These crops were grown inside the FACE ring at increased CO₂ concentration (550 ppm) as well as in open field under ambient CO₂ condition (380 ppm). Surface soil samples were collected prior to sowing and after harvest of crops. Soils were collected from 4 sub-plots inside the ring and also from the control plots. Soil nutrients were analyzed using standard procedures. Results showed that soil MBC was significantly higher inside the FACE ring than control while NH₄⁺-N and NO₃⁻-N were found higher in the control plots (Table 2) in both the crops. Soil organic carbon (SOC) did not show much change with high CO₂ treatment.

Table 2: Impact of elevated CO₂-level on soil nutrient status in rice and wheat crop

Parameters	Ambient	FACE
Rice		
SOC (%)	0.33	0.33
MBC (kg ha ⁻¹)	198	212
NH ₄ ⁺ -N (kg ha ⁻¹)	22.3	19.8
NO ₃ ⁻ -N (kg ha ⁻¹)	12.9	10.3
Wheat		
SOC (%)	0.31	0.32
MBC (kg ha ⁻¹)	138	187
NH ₄ ⁺ -N (kg ha ⁻¹)	37.2	29.7
NO ₃ ⁻ -N (kg ha ⁻¹)	21.9	17.1

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Impact of Climate Change on Insects

Subhash Chander

Introduction

Climate change is a concern of everyone since it poses potential threat to environment, and agricultural productivity and production throughout the world. It has implications for livelihood and survival of human beings. Climate is an important determinant of abundance and distribution of species. The rising concentrations of carbon dioxide will have a variety of direct effects on plants and may also have indirect effects on herbivores and their natural enemies. The climate has profound effects on the populations of invertebrate pests like insects, mites and others and affects their development, reproduction and dispersal systems. Extreme weather events such as intense rainstorms, high wind or elevated temperatures also affect their survival. The climate change impacts on pests may include shifts in species distributions with species shifting their ranges to higher latitudes and elevations, changes in phenology with life cycles beginning earlier in spring and continuing later in autumn, increase in population growth rates and number of generations, change in migratory behaviour, alterations in crop-pest synchrony and natural enemy-pest interaction, and changes in interspecific interactions (Sutherst, 1991; Root *et al.*, 2003). Changes in community structure and extinction of some species are also expected (Thomas *et al.*, 2004).

For species to survive in the changing climates, they must either adapt *in situ* to new conditions or shift their distributions in pursuit of more favourable ones. Many insects have large population sizes and short generation times, and their phenology, fecundity, survival, selection and habitat use can respond rapidly to the climate change. These changes to insect life-history may in turn produce rapid changes in their abundance and distribution. Due to recent climate changes, widespread, generalist species at their cool range margins have expanded their distribution ranges, whereas the ranges of localized, habitat-specialist species

and those at their warm margins have narrowed (Hill *et al.*, 2002; Konvicka *et al.*, 2003). An array of methods including surveys, experiments and modelling have been used to study the impact of climate change on pest abundance and distribution. In this chapter, some of the methodologies being adopted to analyze the climate change impacts on pests are described.

Surveys

Surveys have been used to delineate climate change impacts on species distribution ranges, phenology, migration, winter survival, etc.

Shift in Species Distribution Range

The shift in distribution ranges of insect species can be detected by regular surveys at discrete locations characterized by different latitudes and altitudes. For this, surveys in large transects of around 10 km × 10 km or even in small grids of 1 km × 1 km have been found useful.

Based on a grid survey (10 km × 10 km) in Britain, Hill *et al.* (2002) reported that four butterfly species had gone extinct at the southern margins of their distributions from low elevation and colonized high elevation areas, leading to a mean increase in elevation of 41 m between pre-1970s and 1999.

Regular survey in 11 km × 12 km grids have revealed that in the Czech Republic, the average altitude for 15 butterfly species had increased significantly between 1950 and 2001. Ten species had retracted from low altitudes and 12 had expanded their range at high altitudes with a mean upward shift of 60 m (Konvicka *et al.*, 2003).

Even fine resolution survey in 1 km × 1 km grids in Britain have shown that four northern/montane butterfly species had retreated uphill since 1970 (Franco *et al.*, 2006). Among the four species, *Erebia epiphron* retreated uphill by 130–150 m without any effect of habitat loss on its distribution, while *E. aethiops* and *Aricia artaxerxes* retreated northwards by 70–100 km and showed combined impacts of climate change and habitat loss. On the other hand, *Coenonympha tullia* declined through habitat loss, but showed no latitudinal or elevational shift. It appeared that climate change and habitat decline have been equally responsible for the local extinctions near their range margins.

Changes in Phenology

In addition to the shift in space of species distributions, recent climate change has led to an ecological shift in time, with changes in species' phenology. Changes in insect phenology can be studied through long-term experiments with variable sowing dates for observing the appearance of pests on crops. Likewise, the timing of arrival of insect species can also be recorded through light traps, suction traps or pheromone traps. Analysis of long-term data on phenology would reveal changes in the timings of pest appearance under the climate change.

Suction traps are being used to monitor aphids at The Rothamsted Insect Survey since 1964. Analysis of suction trap data has revealed that spring flights of the peach potato aphid (*Myzus persicae*) started two weeks earlier for every 1 °C rise in combined mean temperature of January and February.

Likewise, long-term data from several insect-recording schemes in Europe and North America have provided evidence for species becoming active, migrating or reproducing earlier in the year due to increases in temperatures that lead directly to increased growth rates or earlier emergence from winter inactivity (Roy and Sparks, 2000). Increasing temperatures have also allowed a number of species to remain active for a longer period during the year or to increase their annual number of generations.

Under the All India Coordinated Rice Improvement Programme (AICRIP) of ICAR, there is widespread network of the Coordinating Centres all over India that collect light trap insect data round the year. Analysis of historical light trap data vis-à-vis current data can provide important information on the impacts of climate change impacts on rice pests.

Insect Migration

The effect of climate change on insect migration can also be analyzed through light trap data and field observations. Based on the data collected through light traps and day time observations in an approximately 0.2 ha area between 1982 and 2005, Sparks *et al.* (2007) analyzed the impact of climate change on migration of lepidopteran insects into England from southwest Europe. Least squares regression was used to compare the total number of migratory species recorded each year with temperature anomalies (differences from the 1961–1990 average) in southwest Europe. The number of migratory species was positively related to

temperature anomalies averaged over March to July and it was suggested that every 1 °C increase in temperature in southwest Europe was associated with an additional migration of 14.4 ± 2.4 species to England.

Winter Mortality

Theoretically, it is hypothesized that the winter survival of insects will be improved by an increase in winter temperature, but the evidence for this hypothesis is rather scarce. Effect of climate change on winter mortality/survival can be examined by collecting long-term data on winter survival at fixed over-wintering sites. Relationship can then be established between winter mortality and temperature.

Kiritani (1971) had examined the winter mortality of adults of *Nezara viridula* in the late March at 16 fixed over-wintering sites from 1962 to 1967 in Wakayama. A regression between winter mortality (Y) and the mean temperature in January (X) [$Y = -16.45X + 147.08$ ($R^2 = 0.6127$, $P < 0.0001$)], suggested that every 1 °C rise around $X = 4$ °C would result in a decrease in winter mortality by about 16.5%.

Experimental Approaches

Direct Impact of Temperature

Comparison of Pests' Favourable Temperature Range with Prevailing and Projected Temperatures

The potential impact of temperature rise on pest prevalence can be known by comparing the current and projected temperature conditions at a location with pest's favourable temperature range. This requires precise determination of favourable temperature range for an insect species. This can be established by rearing insects at a series of constant temperatures ranging from low to high temperatures in BOD incubators or growth chambers with suitable food. Fecundity, hatching, development period, weight, survival and adult emergence should be recorded at as small intervals as possible to account for small differences in development period at different temperatures.

Data on temperature related development period and survival can be used for defining the favourable temperature range for a species and calculating thresholds of development and thermal constant.

A pair of observations on temperature and the corresponding development period can be used for determining the threshold of development or lower threshold (LT) as follows:

$$LT = (T1 \times D1 - T2 \times D2) / D1 - D2$$

where, T1 and T2 are two temperatures and D1 and D2 are the corresponding development periods.

The lower threshold is the minimum temperature at which insect development just starts (Figure 1). Between this and lower lethal temperature, an insect remains in a state of inactivity but resumes activity if it is brought into favourable temperature range. However, once the temperature reaches the lower lethal, organism dies.

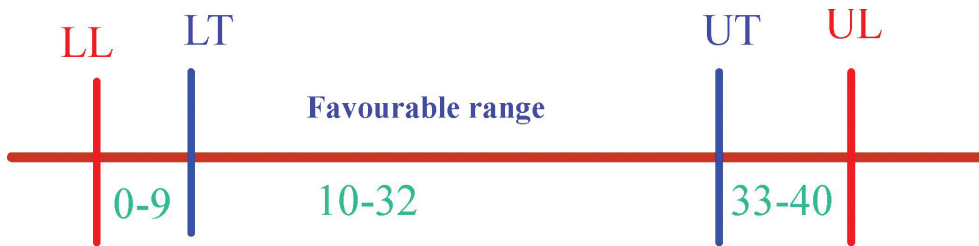


Figure 1. Temperature ranges in relation to insect development (LL – Lower lethal, LT- Lower threshold, UT- Upper threshold, UL- Upper lethal)

Likewise, upper threshold (UT) is that temperature on the higher side that also results in cessation of insect development. Between upper threshold and upper lethal, organism remains in a state of inactivity and resumes activity if it is brought into the favourable temperature range. However, if temperature reaches upper lethal, then organism perishes.

Thermal constant for a particular development stage can be calculated by summing the effective temperatures for the entire duration of development of a particular development stage and consequently, the whole life-cycle. The effective temperature is derived by subtracting threshold of development from daily average temperature.

A comparison of favourable temperature range of an insect species with the prevalent ambient temperature and the projected temperature of a location would

reveal the potential impact of temperature on insect species. If the projected temperature remains within the favourable range of an insect species, then temperature increase would have a beneficial effect on it, increasing its population (Fig. 1). However, if the projected temperature exceeds the favourable temperatures range of the insect species, then its development will be adversely affected, reducing its population and causing damage.

Potential Increase in Number of Generations and Density of Insects

Information on threshold of development and thermal constant can also be used to determine the impact of climate change on the number of generations and density of an insect species. Generally, the number of generations per year is one of the most important parameters that affect the abundance of multivoltine species. Yamamura and Kiritani (1998) have proposed an analytical method to estimate the potential increase in the number of generations under global warming in temperate zones.

$$dN = dT (206.7 + 12.46 (m - T_0)) / K$$

where, dN = Potential increase in the number of generations in a year under global warming; dT = Increase in the annual mean temperature due to global warming; m = Annual mean temperature ($^{\circ}\text{C}$); T_0 = Lower developmental threshold temperature, and K = thermal constant.

In general, assuming a constant temperature rise over the year, species with low T_0 and small K are predicted to have an increasing number of annual generations and an earlier appearance of over-wintering individuals (Yamamura and Kiritani, 1998).

Indirect Effect of CO_2 on Pests

Impact of CO_2 on insect population via host plants can be studied through open-top chambers (OTCs) and free air carbon dioxide enrichment (FACE). The OTCs are essentially plastic enclosures placed around a sample of an ecosystem. Air is drawn into a box by a fan, enriched with CO_2 , and blown through the chamber. Open-top chambers are relatively inexpensive to build because they consist simply of an aluminum frame covered by panels of polyvinyl chloride plastic film. Temperature control is affected by air movement and differential between inside

and outside air temperatures has been found less than 1 °C. Relative humidity within the open tops is directly related to transpiration rate and is always higher than in the external air. OTCs have long been known to modify the environment by altering light intensity, relative humidity, wind speed and direction, and other environmental factors. This is considered a shortcoming for studies on insect and disease occurrence as chambers may interfere with the dispersal of organisms or alter the plant's susceptibility to a given pest. Therefore, to separate out the effect of higher temperature and humidity on insect development from CO₂ effect on it, control should also be in an OTC at ambient CO₂ concentration.

On the other hand, in FACE, plants are grown in open without any enclosure. The FACE technology facilitates modification of the environment around growing plants to future concentrations of atmospheric CO₂ under natural conditions of temperature, precipitation, pollination, wind, humidity, and sunlight. Therefore, FACE field data represent plant responses to concentrations of atmospheric CO₂ in a natural setting. FACE facilities have been developed and deployed ranging from the scale of 1–2m for low-stature crops or ecosystems to those of 10–20m diameter for field crop evaluation to those for young-to medium-aged forest stands and finally to mature trees of basically any size. Ainsworth and Long (2005) have reviewed and summarized FACE research under various FACE facilities.

The effect of higher carbon dioxide concentration on insect multiplication and damage can be studied by releasing a known number of insects on plants in these structures. Periodic observations on insect population and damage would reveal the effect of higher CO₂ on insect development and its damage severity. Alternately, plants grown under elevated CO₂ levels can be fed to insects under ambient CO₂ conditions.

***In-situ* Studies on Pests Inside Structures**

Impact of increased carbon dioxide levels on the oat aphid was examined at the Australian Grains Free Air Carbon Dioxide Enrichment (FACE) site. Aphids that flew into the rings were trapped and monitored during the crop season to observe increase in population under the elevated carbon dioxide levels. It has been predicted that carbon dioxide changes predicted during the next 40 years are likely to have impact on the population size and development of oat aphids. Wheat plants from rings were also observed in laboratory to assess the effect of carbon dioxide changes on crop-pest interactions.

Likewise, FACE facility has also been utilized in India to study pathogen biology and host–pathogen interactions for the biotrophic stripe rust (*Puccinia striiformis*), necrotrophic crown rot (*Fusarium pseudograminearum*) and barley yellow dwarf virus (BYDV). In addition, naturally occurring levels of soil-borne pathogens, *Heterodera avenae*, *Rhizoctonia solani*, *Gaeumannomyces graminis* var. *tritici*, *Pratylenchus neglectus* and *P. thornei*, *F. pseudograminearum* and *F. culmorum* and *Bipolaris* spp. were quantified from the soil using PCR-based diagnostics from each FACE ring both prior to sowing and post-harvesting (Chakraborty *et al.*, 2008).

Hamilton *et al.* (2005) used the FACE technology to create an atmosphere with CO₂ and O₂ concentrations similar to those predicted for the middle of the 21st century. During the early season, soybean grown under the elevated CO₂ atmosphere had 57% more damage from the insects like Japanese beetle, potato leafhopper, western corn rootworm and Mexican bean beetle than those grown under the ambient conditions and even required an insecticide treatment to continue the experiment. Measured increases in the levels of simple sugars in the soybean leaves might have stimulated the additional insect feeding.

Using the ‘Rice FACE’ facility in northern Japan, Kobayashi *et al.* (2006) studied the effect of 200–280 ppm above-ambient CO₂ on rice blast and sheath blight disease for three seasons. Severity of leaf blast (*Magnaporthe oryzae*) was consistently higher at the elevated CO₂ levels in all the three years assessed at two different stages of rice growth. However, severity of panicle blast caused by the same pathogen was not consistently higher at higher CO₂ levels. The incidence of rice plants naturally infected with sheath blight (*R. solani*) was generally higher at the elevated CO₂ concentrations under high nitrogen levels but this trend was not apparent for sheath blight severity.

Gao *et al.* (2008) used OTCs to examine interactions across three trophic levels, cotton (*Gossypium hirsutum*), aphid herbivore (*Aphis gossypii*) and its coccinellid predator (*Propylaea japonica*), as affected by elevated CO₂ concentrations and crop cultivars. Two levels of CO₂, viz. ambient (375 ppm) and double the ambient (750 ppm) were used. Plant carbon:nitrogen (C:N) ratios, condensed tannin, and gossypol content were significantly higher while nitrogen-content was significantly lower in the plants exposed to elevated CO₂ levels compared to those exposed to ambient CO₂. Cotton aphid survival significantly increased with increased CO₂.

concentrations. No significant difference in the survival and lifetime fecundity of *P. japonica* was observed between cultivars and CO₂ concentration treatments. However, stage-specific larval durations of the lady beetle were significantly longer when fed on aphids from the elevated CO₂ concentrations. It was speculated that *A. gossypii* may become a more serious pest under an environment with elevated CO₂ concentrations because of increased survivorship of aphid and longer development time of lady beetle.

Feeding Organisms under Ambient Conditions on Plants Grown under Elevated CO₂ levels

Indirect effect of higher CO₂ levels can also be gauged through feeding the insects under laboratory conditions on plant parts grown under high CO₂ concentration. Observations can be recorded on feeding rate, development period, insect weight and food conversion efficiency.

Rao *et al.* (2009) have conducted feeding trials with two foliage feeding insect species, *Achaea janata* and *Spodoptera litura* using foliage of castor plants grown under four concentrations of CO₂, viz. 700 ppm CO₂ inside open top chamber (OTC), 550 ppm CO₂ inside OTC, ambient CO₂ (350 ppm) inside OTC and ambient CO₂ in the open. Biochemical analysis of the foliage revealed that plants grown under the elevated CO₂ levels had lower N-content, and higher C-content, C/N ratio and polyphenols. Compared to the larvae fed on the ambient CO₂ foliage, the larvae fed on 700 ppm and 550 ppm CO₂ foliage exhibited higher consumption. The 700 ppm and 550 ppm CO₂ foliage was more digestible with higher values of approximate digestibility. The relative consumption rate of larvae increased, whereas the efficiency parameters, viz. efficiency of conversion of ingested food (ECI), efficiency of conversion of digested food (ECD) and relative growth rate (RGR) decreased in the case of larvae grown on 700 ppm and 550 ppm CO₂ foliage. The consumption and weight gain of the larvae were negatively and significantly influenced by the leaf nitrogen, which was found to be the most important factor affecting consumption and growth of larvae.

Indirect effect of CO₂ on pathogen dispersal and infection can be studied by exposing plants grown under different CO₂ environments to natural occurring inoculum in the field. Chakraborty *et al.* (1999) studied the dispersal of and infection by *Colletotrichum gloeosporioides* under ambient weather conditions in

the field on *Stylosanthes scabra* plants that had been raised under ambient and twice the ambient CO₂ concentration in controlled environment chambers. Plants from the two CO₂ environments were exposed to naturally occurring inoculum in the field on different dates, and conidial dispersal and infection were monitored. The enlarged canopy of plants grown under the elevated CO₂ levels trapped more conidia that together with increased humidity in the denser canopy, led to more severe anthracnose than on plants grown under ambient CO₂ level. In a separate experiment, disease was reduced when plants were grown under elevated CO₂ level and inoculated with *C. gloeosporioides* inside the controlled environment.

Temperature Increase through OTCs

The OTCs can be utilized to passively increase the summer temperature in arctic environments and these have proved effective in mimicking the predicted climatic warming. The effect of environmental change on the diversity and abundance of soil arthropod communities (Acari and Collembola) in the Maritime Antarctic and the Falkland Islands has been investigated using OTCs under the framework of the northern boreal International Tundra Experiment (ITEX). OTCs were used to increase the temperature in contrasting communities on three islands along a latitudinal temperature gradient, ranging from the Falkland Islands (51°S, mean annual temperature 7.5 °C) to Signy Island (60°S, -2.3 °C) and Anchorage Island (67°S, -3.8 °C). At each island, an open and a closed plant community was studied. The OTCs raised the soil surface temperature during most months of the year. During the summer, the level of warming achieved was 0.7 °C to 1.7 °C at three sites (Bokhorst *et al.* 2008).

Effect of Rainfall

Distribution and frequency of rainfall may also affect the incidence of pests directly as well as through changes in humidity levels. It is being predicted that under the climate change, frequency of rainfall would decline while its intensity would increase. This would lead to heavy showers and floods on one hand and drought spells on the other. Under such situations, incidence of small pests such as aphids, jassids, whiteflies, mites, etc. on crops may be reduced as these get washed away by the heavy rains.

Armyworm, *Mythimna separata*, reaches outbreak proportions after heavy rains and floods. Lever (1969) had analysed the relationship between outbreaks of armyworm and to a lesser extent *Spodoptera mauritia* (Boisd.) and rainfall from 1938 to 1965 and observed that all but three outbreaks occurred when rainfall exceeded the average 89 cm. The effect of rainfall on pests can be studied by simulating various rainfall intensities through sprinklers. Aphid population on wheat and other crops was adversely affected by rainfall and sprinkler irrigation (Daebeler and Hinz, 1977; Chander, 1998).

Masters *et al.* (1998) have carried out novel manipulations of local climate to investigate how warmer winters with either wetter or drier summers would affect the homopteran insects — a major component of the insect fauna of grasslands. Direct and indirect effects of climate manipulation were observed. It was observed that the supplemented summer rainfall resulted in an increase in the vegetation cover, leading to an increase in the abundance of the insects. Summer drought, however, caused a decrease in the vegetation cover, but this did not lead to a corresponding decrease in the abundance of the insects. Egg hatch and the termination of nymphal hibernation occurred earlier in the winter-warmed plots, but the rate of nymphal development was unaffected.

Modelling Approaches

Impact of climate change would depend upon on complex interactions of climatic and biological factors with technological and socioeconomic changes that are difficult to predict. Therefore, these interactions are not amenable to qualitative analyses. Hence, quantitative (modelling) approaches, which allow investigating multiple scenarios and interactions simultaneously, will become more important for the impact assessment (Coakley and Scherm, 1996). Sutherst *et al.* (1996) have given a framework for such model-based assessment of impacts of climate change. Some of these approaches are discussed here.

Climate Matching

Climate matching involves the calculation of a “match index” to quantify similarity in the climate between two or more locations. The match index is based on variables such as monthly minimum and maximum temperatures, precipitation, and evaporation rates. Software packages for climate matching include BIOCLIM

(Busby, 1991), CLIMEX (Sutherst and Maywald, 1985), HABITAT (Walker and Cocks, 1991) and WORLD. Climate matching may be used for climate change impact assessment by identifying those locations on the globe with a current climate that is similar to the predicted future climate at the location of interest. An analysis of the plant disease problems at the matching locations based on disease distribution maps (Weltzien, 1972) made it possible to predict the future disease risk at the location of interest.

Booth *et al.* (1999) have used climate matching to identify the regions suitable for *Cylindrocladium* leaf blight on *Eucalyptus* spp. in Southeast Asia and around the world. They first established a simple rule for the presence or absence of the disease based on long-term means of temperature and precipitation. This rule was then implemented in a climate matching programme to identify the high-risk regions in Africa, Australia, Latin America, and Southeast Asia under the current climate. Further, two climate change scenarios were run for locations in Southeast Asia. The study suggested an increase in disease risk in northern Vietnam, and eastern Thailand. These predictions were consistent with limited field observations, indicating that severe disease can occur in these regions during the years with extreme weather.

Simulation of Change in Insect Distribution Ranges

CLIMEX software can be used to generate distribution maps of insect species and to assess the possible distributions of these insects in changing climate (Sutherst and Maywald, 1985). It holds the weather data for monthly long-term average maximum and minimum temperatures, rainfall and relative humidity from 2031 meteorological stations world wide from 1931 to 1960. Additional weather data can be added into CLIMEX meteorological database from different meteorological stations.

CLIMEX can predict species potential distribution through weather parameters of its current habitat range or directly by the species biological parameters such as minimum, maximum and optimum temperatures for development. On the basis of biological parameters of the species, CLIMEX generates a map for the potential geographical distribution of the species by counting an eco-climatic index (EI). EI is a numerical value for climatic suitability

and relative abundance of the species. CLIMEX calculates EI from an annual growth index, describing conditions favourable for population growth together with stress factors that limit population growth during unfavourable season in the following manner:

$$EI = [100/52 \sum_{W=1}^{52} (TI_w \times MI_w \times DI_w)] \times [(1 - CS/100) (1 - HS/100) (1 - DS/100) (1 - WS/100)]$$

where, TI_w is the growth index counts for weekly temperature index, MI_w is the moisture index, DI_w is the diapause index and w is the week of the year. Each of the stress indices are calculated on weekly basis and expressed as a sum over the year as annual heat (HS), cold (CS), wet (WS) and dry stress (DS) indices, all indicative of the climatic requirements of the species.

The temperature index is consisted of the lower temperature threshold (DV0), the lower and upper optimum temperatures (DV1 and DV2), and the upper temperature threshold (DV3). Further, the number of degree-days (PDD) required to complete a generation cycle is also used. Four parameters are used in the calculations of the Moisture index (MI); these are lower and upper soil moisture thresholds (SM0 and SM3) and the lower (SM1) and upper (SM2) bounds of optimum range. Diapause index is composed of diapause induction day length (DPD0), diapause induction temperature (DPT0), diapause termination temperature (DPT1) and diapause development days (DPD). The stress indices used are heat stress (HS), dry stress (DR) and wet stress (WS).

The eco-climatic index (EI) values range from 0 to 100, describing climatic suitability of the location for the species. At the EI value of 0, the species cannot establish a viable population at the location. Values over 20 indicate a very favourable climate for the species.

Vanhanen *et al.* (2007) have used CLIMEX modelling software to predict the future distribution ranges of two Central European serious forest pest species, the nun moth (*Lymantria monacha*) and the gypsy moth (*L. dispar* L).

Empirical Models

Empirical models based on long-term data on pest incidence and weather variables can be used to assess the likely impact of climate change on pest status in a region.

Dynamics of four diseases of wheat and rice over time were examined by the regression analysis to find their relationship with recent increases in mean and minimum temperatures (Yang *et al.* 1998).

Boag *et al.* (1991) used the data from the European Plant-Parasitic Nematode Survey to assess the possible impacts of climate warming on the geographical range of virus-vector nematodes. Initial analyses of nematode presence-absence data suggested a close association between mean July soil temperature and nematode distribution. Based on this result, the authors predicted that the climate change could result in increased nematode and virus problems in northern Europe.

Jahn *et al.* (1996) utilized long-term plant disease monitoring records collected by the State Plant Protection Service in Germany to develop empirical climate-disease models for 15 individual host-pathogen combinations. These models were then used with various climate change scenarios to predict the possible changes in infestation levels in a future climate.

Chander *et al.* (2003) have related the aphid incidence on barley crop variety 'DL-70' during *rabi* season from 1985-86 to 1999-2000 to weather parameters. There was appreciable inter-annual variation in the aphid incidence on barley, perhaps due to inter-annual climatic variability. The aphid population on barley exhibited a declining trend with time. The aphid population showed a negative relationship with the January mean minimum temperature ($r = -0.37$, Figure 2), while it was not related to the February mean minimum temperature. The February total rainfall and aphid population were also found to be negatively related ($r = -0.27$, Figure 2). Therefore, the rise in minimum temperature and more intense rains in future as speculated might reduce aphid incidence on barley.

Simulation Models

Simulation models have been used widely to assess the impact of climate change on yield of various crops in different agro-ecological zones. However, biotic stresses like insects, pathogens, and weeds have largely been ignored in these studies (Teng *et al.*, 1996). Due to this drawback, the development of linked pest-crop models is an important objective within the overall goal of developing a predictive capability for agricultural impact assessment and mitigation (Sutherst *et al.*, 1996;

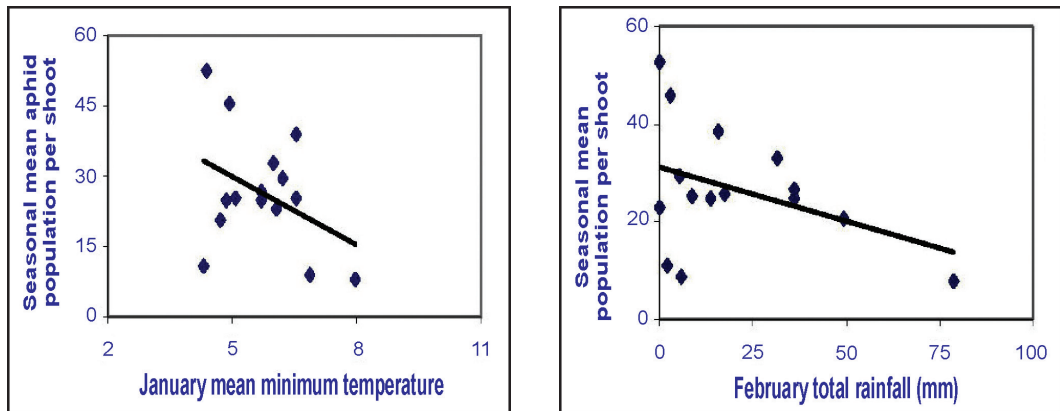


Figure 2. Effect of minimum temperature and rainfall on incidence of barley aphids

Teng *et al.*, 1996). This requires that emphasis be laid on population dynamic simulations and their coupling with crop growth simulation models.

Simulation of Population Dynamics

Insect population dynamics model can be devised based on various bio-ecological factors, viz. fecundity, sex ratio, migration, abiotic and biotic mortality factors, threshold of development and thermal constant. Chander *et al.* (2009) have developed such a model for rice gundhi bug, *Leptocoris acuta*, which is comprised

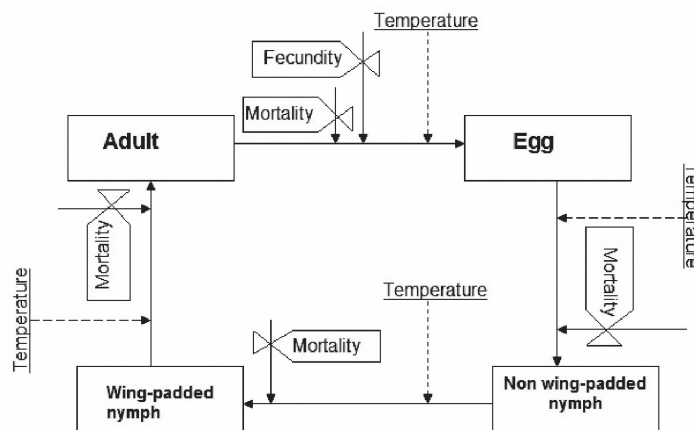


Figure 3. Relational diagram showing the variables of population dynamics simulation model of rice gundhi bug

of state, rate, driving and auxillary variables (Figure 3). State and rate variables approach was followed in developing the model. Insect population converted from one stage to another in proportion to the ratio of effective temperature to thermal constant of that stage and stage-specific mortality. Depending upon the rate of population change, total insect number in each developmental stage was updated daily.

The model was used to simulate the impact of global warming on the rice bug by altering daily minimum and maximum temperatures. It could be concluded that up to 1 °C rise in daily average temperature over the present temperature of Delhi would not affect the gundhi bug population much, but further increase would cause appreciable decline in its population.

Coupling of Population Dynamics Model to Crop Growth Simulation Model

The population dynamics model can be coupled to crop growth model at the appropriate level of plant processes, depending on the pest damage mechanisms. The damaging pest stage affects plant growth and yield based on its number and feeding rate of individuals. Crop-pest model can then be used to analyze the impact of climate change on crop productivity, insect dynamics as well as crop-pest interactions.

Assessing Impact of Climate Change

The impact of rise in and temperature and CO₂ levels on crop productivity can be assessed by increasing the temperature and CO₂ concentrations in model simulations. Likewise, the temperature rise will also affect insect development; however CO₂ does not affect insect development directly but affects it indirectly through the host plant. Therefore, effect of CO₂ on insect development has to be accounted for by changing the insect feeding rate accordingly.

InfoCrop-maize, coupled with holometabolous population dynamics model, was used to simulate population dynamics of maize stem borer, *Chilo partellus* as well as crop-pest interactions (unpublished data). Maize stem borer acts as a stand reducer and causes loss of leaf area, leaf weight, stem weight and panicle weight to the crop. Larva being the damaging stage of the pest, larval population from population dynamics model was linked to the processes of leaf area, leaf weight, stem weight and ear weight in the crop model. Depending upon larval

population and feeding rate of a larva, these crop growth processes were affected. The coupled model was calibrated and validated with field experimental data on larval population and the corresponding maize yield. Validated model was used to simulate effect of 0.5-3.0 °C rise in both maximum and minimum temperatures compared to the ambient conditions on pest dynamics as well as crop-pest interactions. Simulation of pest dynamics showed a decline in the pest severity thereby reducing the pest-induced yield losses under global warming. However, maize productivity also depicted reduction even without pest stress under climate change, indicating that despite reduction in pest stress, crop productivity as such may be adversely affected by the global warming.

Climate change impact assessment through coupled rice brown plant hopper (BPH)- InfoCrop model, in the light of the projected climate change scenario for Indian subcontinent, showed a decline in BPH population of 3.5% by 2020 and of 9.8-14.0% by 2050, during the rainy season at New Delhi, while the pest population exhibited only a small decline of 2.1- 3.5% during winter at Aduthurai even by 2050. Simulation attributed the decline in BPH population to reduction in fecundity and survival. Concomitant to its population decline, the BPH-induced yield loss also indicated a declining trend with temperature rise. However, the study considered the effect of only CO₂ and temperature rise on the BPH population and crop yield, and not that of probable changes in the feeding rate and adaptive capacity of the pest (unpublished data).

The impact of climate change on pink borer, *Sesamia inferens*, population and crop-pest interaction was analyzed through coupled InfoCrop model. A rise of 0.5-1.0 °C temperature showed a small effect on various pest developmental stages, but a further increase had a significant adverse effect on them. In accordance with climate change projections for Indian subcontinent during *kharif* season, the study indicated that population of *S. inferens* developmental stages might decline to the extent of 5.82-22.8% by 2020 and 19.01-42.74% by 2050. Following decline in pest population, yield loss due to *S. inferens* also revealed a declining trend with temperature rise (unpublished data).

Combined effect of increased temperature, elevated UV-B radiation and rice blast disease (*Pyricularia grisea*) on rice yield was assessed using a coupled simulation model (Luo *et al.*, 1997). The model consisted of physiological rice growth model and a leaf blast epidemic simulator that simulated quantitative effects of leaf blast on photosynthesis and biomass production. Climate change

was imposed by increasing the mean temperature in fixed increments and by either including or omitting the effects of UV-B on the host and pathogen.

Kaukoranta (1996) has developed degree day models for the emergence of potatoes and the date of late blight outbreaks in Finland. The two models were coupled and validated and used with various temperature change scenarios to predict the possible changes in potato yield and yield losses caused by late blight in a warmer climate. The results have suggested that tuber yield could increase by 2 t /ha/1 °C warming in the absence of late blight. This yield gain was, however, nullified by the presence of late blight due to occurrence of disease outbreak 4 to 7 days earlier and the lengthening of crop susceptibility period by 10 to 20 days/1°C warming.

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Crop-Weed Balance Studies under Climate Change

TK Das, AR Sharma and H Pathak

Over the years, increasing concentrations of carbon dioxide (≥ 370 ppm) and other active green-house gasses (CFCs, CH_4 , N_2O , NO_2 , etc.) have led to global warming and the associated greenhouse effect. Weeds grown in association with the crops are also exposed to changes in the environment. They are equally and may be differently influenced due to these changes as different species of weeds grow together with a crop. The responses of crop and weeds to increased CO_2 level and temperature are being studied worldwide. The variations in the responses of C_4 and C_3 plants (both crops and weeds) have been noted under such situations. Composite weeds in the crop fields having variable proportions of C_4 and C_3 plants are likely to undergo dynamics in weeds insurgence and shift of weeds in favour of certain species in course of time. Increased CO_2 level may stimulate photosynthesis in some weeds, leading to higher growth of rhizomes and other storage organs in perennial weeds, higher seed production in annual weeds, etc. and make their control difficult concurrently or over the seasons/ years. Thus, an appropriate technology towards controlling increasingly more difficult perennial weeds will be the important paradigm in future weeds research. Climate change is likely to trigger differential growth in crop and weeds and may have more implications on weed control across crops and cropping systems. Some emerging areas of weed research relevant under climate change scenarios are discussed in this chapter.

Weed Biology, Ecology and Interference Studies

Understanding of the biology, ecology and succession of weed species are of immense importance for their management. In this context, periodicity, dormancy, viability/longevity, weed seed bank appraisal, population/species

dynamics, IVI, could be studied. Weed interference potential in composite stand of weeds as well as of single weed species, yield loss, and economic threshold, and period threshold for weed competition need to be investigated under the changed climate scenario.

Selective Allelopathy and Self-Supporting Weed Management

Studies involving allelopathic crop residue mulches (e.g., maize, sorghum, wheat, barley or rye, etc.) may help to mitigate adverse climatic effects. Effective utilization of such crop residue mulches can act as self-supporting weed management (e.g., rice) for the concurrent as well as rotational crops.

Soil Solarization Studies

Soil solarization plays a big role in the management of weeds, nematodes and pathogens under the conditions of increased temperature. It can be incorporated in the schedule of integrated weed management (IWM) and integrated pest management (IPM). However, the thickness and colour of polyethene, time and duration of solarization, effect on beneficial micro-organisms and nutrient mineralization, and supplementary treatments to be superimposed or followed after solarization across situations need to be more characterized / refined under the changing climate.

Chemical Weed Control Studies using Old and New Molecules of Herbicides

Climate change, particularly increased temperature may have profound impact on the control of composite, parasitic, aquatic, and invasive weeds using herbicides in crops and non-cropped situations. Studies on the ED_{50} or GR_{50} value and efficiency of herbicides are of paramount importance under this situation. Monitoring of residues in soil, water and plants may add another dimension of research. The following studies may have priority: (i) herbicide bio-efficacy, biochemical selectivity and non-target toxicity of the old and new herbicides and their formulations; (ii) herbicide resistance management; and (iii) herbicide-resistant crops (transgenics) and their performance evaluation.

Integrated Weed Management

Integrated weed management (IWM) is the recent and more acclaimed aspects of long-lasting weed management programme in crops and non-cropped situations.

Conservation Agriculture and Weed Management

Weed management under minimal and zero tillage poses a big challenge to crop production and appears to be another important aspect of research across crops and situations. Resource conserving techniques need to be blended with other options towards better weed control under conservation agriculture.

Remote Sensing and Site-Specific Weed Management

Combined use of remote sensing, GIS (Geographic Information System) and GPS (Global Positioning System) is a powerful tool in detecting, mapping and monitoring the spread of weeds over inaccessible areas. Identification of weed species using remote sensing in range or wild range lands can be achieved. Site-specific weed management (SSWM) may be undertaken using these tools. Computer-analyzed video images of the digital data can provide the area estimates of weeds.

Observations

Observations vary based on the nature of studies. Generally, a research, embracing a number of related disciplines or inter-disciplinary in nature should be envisaged in every research programme. Agronomical/ecological, microbiological, physiological/ biochemical and chemical observations enlisted in Table 1 may be adopted as applicable.

Methodologies for Determination

Agronomic/Physiological Parameters/Observations

Mean Weed/Crop Growth Rate ($\overline{WGR}$ or $\overline{CGR}$)

It is the rate of increase in dry weight per unit ground area per unit time (Radford, 1967; Das 2008; Heggenstaller *et al.*, 2009), and is expressed as g m⁻²(ground area) day⁻¹. It can be calculated using Equation (1):

$$\overline{WGR}/\overline{CGR} = (W_2 - W_1)/(t_2 - t_1) \quad \dots(1)$$

where, W_1 and W_2 are the dry weights of plants per m² (land area) at t_1 and t_2 DAS, respectively; and $t_2 > t_1$.

Table 1. Observations to be recorded across disciplines

S. No.	Disciplinary boundary	Observations
1.	Agronomical/ ecological	Weeds: Individual species-wise, category-wise (grassy/ monocots, broad-leaved/dicots) and total/composite weed population and dry weight, tillers/branching (as applicable), number and weight of seeds per plant, 1000-seed weight, seed germination, periodicity/flushes of germination, dormancy, viability/longevity, relative frequency, relative density, relative dominance, abundance, IVI, similarity and dissimilarity index, shift in flora, herbicide injury symptoms, time for developing biotype resistant to a herbicide, weed control index and efficiency Crop: Plant stand count, dry weight, tillers/branching (as applicable), nodule count and dry weight, root biomass, yield attributes and yields, harvest index, protein content & harvest, oil content & yield, fertilizer use efficiency, phytotoxicity rating and weed index
2.	Microbiological	Soil: Microbial biomass carbon; population of <i>Rhizobia</i> , fungi, bacteria, actinomycetes and nematodes; dehydrogenase, asparaginase, glutaminase and amidase activity; Crop: Biological nitrogen fixation, total nodule N content
3.	Physiological/ biochemical	Crop & Weeds (both): Growth parameters (WGR & CGR), RGR, NAR, leaf area index and rate of photosynthesis; Crop only: Superoxide dismutase, catalase, ascorbate peroxidase activities in crop plants; fate of herbicide in crops - selectivity/ tolerance or susceptibility
4.	Chemical	Soil: Estimation of $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$ and total N, residues and fate of herbicides in soil Crop and Weeds (both): nutrient (N, P and K) concentration, uptake and total uptake (grain <i>plus</i> straw / stover)
5.	Socio-economical	Monetary advantage, benefit-cost economics, adoption and social impact

Mean Weed/Crop Relative Growth Rate (RGR)

Mean relative growth rate is the rate of increase in dry weight per unit dry weight present per unit time (Equation 2) and is expressed as $\text{g g}^{-1} \text{day}^{-1}$. The increase is continuous and analogous to the accumulation of capital invested at compound interest (Blackman, 1919).

$$\overline{\text{RGR}} = (\ln W_2 - \ln W_1) / (t_2 - t_1) \quad \dots(2)$$

where, W_1 and W_2 are the dry weights of plants per m^2 (land area) at t_1 and t_2 are DAS, respectively, and $t_2 > t_1$; $\ln$ = Natural logarithm ($\ln = \log_e^Y = 2.303 \times \log_{10}^Y$)

Net Assimilation Rate (NAR)

It is the rate of increase in dry weight of plants per unit leaf area per unit time (Equation 3) (Das, 2008; Heggenstaller *et al.*, 2009). It is an estimate of the assimilatory efficiency of leaves, and is expressed as $g\ m^{-2}$ (leaf area) day^{-1} . It is calculated as follows:

$$NAR = [(W_2 - W_1)(\ln L_2 - \ln L_1)] / [(t_2 - t_1) (L_2 - L_1)] \quad \dots(3)$$

where, L_1 and L_2 are the leaf areas of plants at t_1 and t_2 DAS, respectively.

Leaf Area and Leaf Area Index (LAI)

Since the crop yield is expressed per unit of ground area instead of per plant, the leaf area existing on unit land area is proposed by Watson (1958). Thus, leaf area index is the ratio of leaf area of plants to land area occupied (Equation 4). It is a fulcrum between net assimilation rate (NAR) and yield (Das, 2008; Heggenstaller *et al.*, 2009).

$$LAI = (\text{Leaf area of plants}) / (\text{land area occupied by those plants}) \quad \dots(4)$$

(a) The leaf area can be measured using the following methods:

(i) Leaf Area Meter : It is the most useful, quick, authentic and supportive method.

(ii) By using Formula :

$$\text{Leaf area per leaf} = (\text{Length} \times \text{maximum breadth} \times 0.65)$$

$$\text{Leaf area per plant} = (\text{Length} \times \text{maximum breadth} \times 0.65 \times \text{number of leaves per plant})$$

The constant 0.65, proposed by Lazarove (1965), is used for cereal crops, e.g. rice, wheat, barley, oat. In all these crops, the length and breadth of the 3rd leaf from the top of main shoot are measured at each successive phonological stage. In maize, sorghum, and pearl millet having wider leaves, the value of constant is 0.75 and accordingly the formula becomes:

$$\text{Leaf area per leaf} = (\text{Length} \times \text{maximum breadth} \times 0.75)$$

Specific Leaf Area (SLA)

Specific leaf area is defined as “ the ratio of leaf area (L) to leaf dry weight (Lw) (Equation 5):

$$SLA = (L/Lw) \quad \dots(5)$$

$$SLA = 1/2[(L_1/Lw_1) + (L_2/Lw_2)]$$

where, L_1 and L_2 are leaf areas and Lw_1 and Lw_2 are leaf dry weights at time t_1 and t_2 , respectively.

Light Interception (LI)

Light interception (Equation 6) gives indications of the canopy coverage of a crop and indirectly weeds growth and is determined using a lux meter between 13:00 and 14:00 hours on cloudless days to minimize the proportion of diffused light. Light incidences above the canopy, and at the ground level are measured from two locations in each plot.

$$LI(\%) = [(Light\ above\ canopy - light\ at\ groundlevel) \times 100] / (Light\ above\ canopy) \quad \dots(6)$$

Harvest Index (HI)

Harvest index (Donald, 1963) is the proportion of economic yield (grain yield or yield of economic produce) to total biological yield (Equation 7). Donald and Hamblin (1976) have emphasized the importance of harvest index in agronomic and plant breeding studies. It characterizes the movement of dry matter to economic part of the plants. It is usually expressed as per cent based on total harvest at maturity and its value is less than 100. When expressed as a ratio, it is less than unity and does not have any unit. The biomass should be air-dried to the desired moisture content or if wet, oven-dried.

$$HI = [(Economic\ yield) \times 100] / (Total\ biological\ yield) \quad \dots(7)$$

Weed Control Parameters/Observations***Weed Control Efficiency (WCE)***

Weed control efficiency (Equation 8) compares different methods/ treatments of weed control on the basis of their effect on weed density (Mani *et al.*, 1973; Das,

2008). It reveals methods/ treatments efficiency based on reduction in weed density.

$$WCE (\%) = [(WP_c - WP_t) \times 100] / WP_c \quad \dots(8)$$

where, WP_c and WP_t are weed populations (No./m²) in the control and treated plots, respectively.

Weed Control Index (WCI)

Weed control index (Equation 9) compares different treatments of weed control on the basis of weed dry weight (Misra and Tosh, 1979). It is a more reliable estimate of weed competition/control in crops than weed control efficiency.

$$WCI (\%) = [(WDW_c - WDW_t) \times 100] / WDW_c \quad \dots(9)$$

where, WDW_c and WDW_t are the dry weights (g/m²) of weed in the control and treated plots, respectively.

Weed Index (WI)/Weed Competition Index (WCI)

Weed index (Equation 10) is a measure of the crop yield loss across treatments in comparison to a weed-free plot or in certain cases, the minimum weed-infested plot (Gill and Vijayakumar, 1969).

$$WI = [(Y_{wf} - Y_t) \times 100] / Y_{wf} \quad \dots(10)$$

where, Y_{wf} is the crop yield under weed-free check; and Y_t is the crop yield in the treatment.

Weed Smothering Efficiency (WSE)

Weed smothering efficiency (Equation 11) suits best under intercropping to determine the weed smothering abilities of different intercrops adopted in certain crops of prime interest.

$$WSE (\%) = [(MD_w - ID_w) \times 100] / MD_w \quad \dots(11)$$

where, MD_w is the average dry weight of weeds in main/sole crop; and ID_w is the average dry weight of weed under intercropping situation. To have more accuracy, observations may be collected from 2-3 spots within a plot or treatment per replication and averaged out.

Herbicide Efficiency Index (HEI)

Herbicide efficiency index (Equation 12), given by Krishnamurthy *et al.* (1975), is as follows:

$$\text{HEI} = [(Y_T - Y_C) \times 100 / Y_T] / [(WDW_T \times 100) / WDW_C] \quad \dots(12)$$

where, Y_T and Y_C are crop yields from the treated and weedy checks; WDW_T and WDW_C are the dry weights of weed in the treated and weedy check plots, respectively.

Fresh Weight - Dry Weight Ratio and Moisture Content

Although lower the dry weight of weeds, higher is the bio-efficacy of the treated herbicide, it does not hold true always. Two new parameters, F-D ratio (fresh weight and dry weight ratio) (Equation 13) and moisture content (Equation 14) of the weed sample treated with herbicides have been suggested for a better appraisal of herbicide bio-efficacy (Das, 2001). They require to be adopted along with fresh weight and dry weight for a better appraisal of the herbicide bio-efficacy.

$$\text{F - D ratio} = (\text{Fresh weight of weed sample}) / (\text{Dry weight of weed sample}) \quad \dots(13)$$

$$\text{Moisture (\%)} = [(\text{Weed fresh weight} - \text{Weed dry weight}) \times 100] / (\text{Weed dry weight}) \quad \dots(14)$$

Phytotoxicity Rating

Herbicide on application to crop field producing certain injury symptoms mainly on weeds and in negligible or undetectable scale on crop plants and inducing graded response of growth reduction or death of plants across plant species is phytotoxicity. Phytotoxicity scale generally adopted are 0-5, 0-10, 1-5 or 1-10. Observations should be recorded separately for weeds and crop. Phytotoxicity may be judged by at least two persons standing on either side of the herbicide-treated plot. The persons should be literate in weed science and should have knowledge of the mode of action and usual injury symptoms of the herbicide under question.

Weed Persistence Index (WPI)

Weed persistence index (Equation 15) and other indices (Equations 16, 17, 18 and 19) has been derived recently (Mishra and Misra, 1997), which has got enough relevance to study the aspect of weed management on comparative basis.

$$WPI = \frac{[(\text{Weed density in control plot}) \times (\text{Weed dry weight in treated plot})]}{[(\text{Weed density in treated plot}) \times (\text{Weed dry weight in control plot})]} \quad \dots(15)$$

Crop Resistance Index (CRI)

It is given by Equation (16):

$$CRI = \frac{[(\text{Crop dry weight in treated plot}) \times (\text{Weed dry weight in control plot})]}{[(\text{Crop dry weight in control plot}) \times (\text{Weed dry weight in treated plot})]} \quad \dots(16)$$

Pest/Weed Management Index (PMI)

It is calculated using Equation (17):

$$PMI = (\text{Per cent crop yield over control}) / (\text{per cent control of weeds or other pests}) \quad \dots (17)$$

Agronomic Management Index (AMI)

It is calculated using Equation (18):

$$AMI = \frac{[(\text{Per cent crop yield over control}) - (\text{per cent control of weeds/other pests})]}{[(\text{per cent control of weeds/other pests})]} \quad \dots(18)$$

Integrated Pest/Weed Management Index (IPMI)

The IPMI is obtained using Equation (19):

$$IPMI = [(PMI + AMI)/2] \quad \dots(19)$$

Determination of Crop Yield and Yield Loss and Economic Threshold

Economic threshold is the density at which the cost of control measures equals the benefits (Das, 2008). Crop-specific threshold is used as an aid to decision-making. The density per unit area (Cousens, 1985 a; b) and relative leaf area (Kropff and Spitters, 1991; Kropff and Lotz, 1993) of a weed is usually considered

for working out the economic threshold in a certain crop. Also, there are simulation models available for such calculations. However, economic threshold based on composite weed population in the fields is a rare possibility and hardly exists.

Simulation of Crop Yield and Yield Loss

Crop Yield versus Weed Density

The effect of weed density on crop yield is evaluated using simple empirical models. The crop yield-weed density response is asymptotic (Cousens, 1985 a; b), and, therefore, a rectangular non-linear hyperbolic regression model (Equation 20) is used to analyze the relationship between crop yield (Y) and weed density (d):

$$Y = Y_{wf} [1 - id/100(1 + id/A)] \quad \dots(20)$$

where, Y is the simulated crop yield in a particular weed density; Y_{wf} is the estimated/ observed weed-free crop yield; i is the per cent yield loss per unit weed density (d) as $d \rightarrow 0$, and A is the asymptotic value of the maximum yield loss (%) as d (density) $\rightarrow \infty$.

Data are fitted to non-linear equations using an iterative method in the 'SPSS' package (Norris, 1992), and the above-mentioned parameters are estimated. The data and fitted curves are presented in terms of per cent yield loss (Y_L) using Equation (21):

$$Y_L = [id/(1+id/A)] \quad \dots(21)$$

where, Y_L is the yield loss (%) and i, d and A have been defined above.

Crop Yield versus Weed Relative Leaf Area

The empirical model (Equation 22) relating the crop yield loss to the relative leaf area of weed is also employed to evaluate the crop yield losses (Kropff and Spitters, 1991; Kropff and Lotz, 1993).

$$Y_L = qL_w/[1 + (q - 1)L_w] \quad \dots(22)$$

where, Y_L is the relative yield loss; L_w is the relative leaf area of weed (i.e. leaf area of weed divided by the total leaf area of crop and weed per unit area); and q is the relative damage coefficient.

Economic Threshold (ET) of Weed

The economic threshold (ET) of a weed is determined using the quadratic Equation (23), as suggested by Cousens (1987):

$$1 + (i/A)[2 - H - (YPAH/C)]T + (i/A)^2 (1 - H) T^2 = 0 \quad \dots(23)$$

where, 'i' and 'A' are as defined above, and were calculated using Equation (1); Y is the weed-free crop yield; P is the unit price of economic produce of crop; H is the efficiency of herbicide; C is the cost of weed control; and T is the economic threshold density.

Determination of Microbiological Parameters

Enumeration of Microbial Populations

Fungi, bacteria and actinomycetes populations are counted by serial dilution and agar/ pour plate techniques using 1 mL of soil solution for plating (Das *et al.*, 2010). Martin Rose Bengal agar medium, soil extract nutrient agar medium, and Ken Knight's medium are used for the isolation and supporting the growth of fungi, bacteria and actinomycetes, respectively (Subba Rao, 1977). Once the serial dilution and spreading of the soil solution on the respective plates are done, the plates are incubated at 30 °C. The populations of bacteria, fungi and actinomycetes per plate are observed in 2, 5-7 and 7-10 days of incubation, respectively.

Dehydrogenase Activity (DHA)

Six grams of soil are mixed properly with 2.5 mL of sterile distilled water and 1.0 mL of 3% aqueous solution of 2, 3, 5-triphenyltetrazolium chloride (TTC). It is incubated at 30 °C for 24 h and is extracted with methanol. TTC is a colourless liquid and acts as an electron acceptor. DHA was estimated by monitoring the rate of production of red colour due to 1, 3, 5-triphenyl formazan (TPF) from TTC (Casida, 1977). The concentration/ absorbance of red methanolic solutions of TPF was estimated at 485 nm against the extract from a non-TTC soil blank by using Spectronic 20 colorimeter. The values obtained were compared against a formazan (Calbiochem) standard curve prepared with methanol and were expressed as μgTPFg^{-1} of oven-dried soil day^{-1} .

Physiological/Biochemical Observations

Acetylene Reduction Assay (ARA)

Acetylene (C_2H_2) reduction (Hardy *et al.*, 1973) indicates the nitrogenase activity and rates of biological nitrogen fixation in the nodules of soybean plants. In the process, ethylene (C_2H_4) is evolved due to reduction of C_2H_2 . This gives an indication of nitrogenase activity. Root nodules of 45-day old soybean plants are

detached along with root portions and incubated in 10% C₂H₂ for 45 minutes. One mL of air sample is withdrawn and injected into a Nucon gas chromatograph (model 5765, New Delhi, India). The resulting peak area of sample is noted and estimation is done using the following formula:

Milli moles C₂H₄ produced per gram of nodule fresh weight per hour =

$$= \frac{\text{Peak area of sample}}{\text{Peak area of standard C}_2\text{H}_4} \times \frac{\text{Conc. of Standard C}_2\text{H}_4}{\text{Weight of sample}} \times \frac{\text{Air space volume}}{\text{Time of incubation in hour}}$$

Photosynthesis Rate

Five leaves, which are third leaf in position from the apex, are chosen from five randomly-selected plants in each treatment. The leaves are inserted separately into a cuvette/ chamber for measuring photosynthesis. A portable infrared gas analyzer (IRGA) in closed mode (Ehleringer and Cook, 1980) is used to measure the rate of photosynthesis of plants between 10:00 and 11:30 AM by providing artificial light source of intensity 1000 $\mu\text{molm}^{-2}\text{s}^{-1}$ at 40 DAS. CO₂ absorbs radiation in the intermediate infra-red wavebands. IRGA measures the reduction in transmission of infra-red wavebands caused by the presence of a gas between the radiation source and a detector. The reduction in transmission is a function of the concentration of the gas. Absolute concentrations of CO₂ in the analysis and reference lines are determined by comparison with air in an internal loop in which CO₂ has been chemically removed. CO₂ concentration should be close to the global mean of about 370 ppm.

Superoxide Dismutase (SOD) and Ascorbate Peroxidase (APX) Activity

Enzyme Extract Preparation

One gram soybean leaf is frozen in liquid nitrogen to prevent proteolytic activity. Then leaf sample is ground with 10 mL extraction buffer (0.1 M phosphate buffer, pH 7.5, containing 0.5 mM EDTA and 1 mM ascorbic acid). Extract is passed through four layers of cheesecloth and filtrate is centrifuged for 20 min at 15000 rpm. The supernatant is used as enzyme.

Superoxide Dismutase (SOD) Assay

The SOD activity is estimated by recording the decrease in optical density of formazone owing to superoxide radical and nitro-blue tetrazolium dye by the

enzyme (Dhindsa *et al.*, 1981). Three millilitres (final volume) of the reaction mixture is prepared with 13.33 mM methionine (0.2 mL of 200 mM), 75 μ M nitroblue tetrazolium chloride (NBT) (0.1 mL of 2.25 mM), 0.1 mM EDTA (0.1 mL of 3 mM), 50 mM phosphate buffer (pH 7.8) (1.5 mL of 100 mM), 50 mM sodium carbonate (0.1 mL of 1.5 M), 0.05 to 0.1 mL enzyme and 0.9 to 0.95 mL of water. Reaction is started by adding 2 mM riboflavin (0.1 mL) and placing the tubes under two 15 W fluorescent lamps for 15 min. A complete reaction mixture without enzyme, which gives the maximal colour serves as the control. Switching off the light and putting the tubes into dark stop the reaction. A non-irradiated complete reaction mixture serves as a blank. The absorbance is recorded at 560 nm, and one unit of enzyme activity is taken as that amount of enzyme, which reduces the absorbance reading to 50% in comparison with tubes lacking enzyme.

Ascorbate Peroxidase (APX) Assay

The APX activity is measured by recording the decrease in optical density due to ascorbic acid at 290 nm (Nakano and Asada, 1981). Three mL (final volume) reaction mixture containing 50 mM potassium phosphate buffer (pH 7.0) (1.5 mL of 100 mM), 0.5 mM ascorbic acid (0.5 mL of 3.0 mM), 0.1 mM EDTA (0.1 mL of 3.0 mM), 0.1 mM H_2O_2 (0.1 mL of 3.0 mM), 0.1 mL enzyme and 0.7 mL water. Reaction is started with the addition of 0.2 mL of H_2O_2 . Decrease in absorbance for a period of 30 sec is recorded at 290 nm in a UV-visible spectrophotometer. Activity is expressed by calculating the decrease in ascorbic acid content by comparing with a standard curve drawn with known concentrations of ascorbic acid (Nakano and Asada, 1981).

Chemical Analysis of Herbicide Residues (e.g., Pendimethalin and Metribuzin)

Soil Sampling

Soil is to be collected from 0-15 cm depth with the help of a tube auger from randomly selected 5-10 spots in each plot and composited for estimating residues (e.g., pendimethalin and metribuzin).

Extraction and Clean-up for Herbicide

Pendimethalin

A 100 g representative soil sample is extracted with methanol + concentrated HCl (98 + 2 by volume; 300 mL) by shaking on a horizontal shaker for 1 h

(Kulshrestha *et al.*, 2000). The contents are filtered under vacuum; the filtrate is concentrated, transferred to a separating funnel and diluted with water (150 mL) and partitioned with hexane (70+50+30 mL). The organic phase is dried over anhydrous Na_2SO_4 (5 g) and solvent evaporated. For residue estimation, it is dissolved in hexane and analyzed using gas chromatography (GC).

Metribuzin

A 100 g representative soil sample is extracted with methanol (200 mL); diluted with water; and extracted with dichloromethane (200+100+100 mL) using separating funnel (Kulshrestha and Singh, 2001). The organic layer is separated and dried over anhydrous Na_2SO_4 (10 g) through a fluted filter paper. The solvent is evaporated to dryness on a rotary evaporator. The remaining aqueous phase is discarded. Residues are re-dissolved in hexane: acetone (4:1) prior to injection to GC.

Gas Chromatography (GC)

Residues of pendimethalin (Kulshrestha *et al.*, 2000) and metribuzin (Kulshrestha and Singh, 2001) are estimated separately on a Hewlett Packard gas chromatograph (model 5890) fitted with a ^{63}Ni electron capture detector. Aliquots (3 μL) are injected into megabore column (20 m x 0.53 mm; 20 μm film thickness) packed with HP-17. Purified N_2 at 25 mL/min flow is the carrier gas. The column, injector and detector temperatures for analyzing the residues on GC are: 210 °C, 235 °C and 275 °C, respectively for pendimethalin; and 185 °C, 250 °C and 275 °C, respectively for metribuzin. Under these conditions, pendimethalin and metribuzin give sharp peaks at a retention time (Rt) of 3.45 min and 3.54 min, respectively.

Recovery Studies

Recovery experiments for pendimethalin and metribuzin from soil are conducted at two fortification levels, viz. at 0.1 and 0.5 $\mu\text{g g}^{-1}$ of soil. Following the above procedures of extraction and analysis, the recovery of pendimethalin and metribuzin ranges between 85-87% and 75-82%, respectively.

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Section IV

Adaptation Strategies to Climate Change

Biochemical Traits of Crops for Adaptation to Climate Change

Ranjeet R Kumar and Suneha Goswami

Introduction

Climate and agriculture are intensely interrelated global processes and therefore a change in climate affects agricultural production (IPCC, 2007). One such change is global warming which is projected to have significant impacts on environment affecting agriculture, including higher carbon dioxide emission, rise in atmospheric temperature, higher glacial run-off, changed precipitation and the interaction of these elements. These conditions determine the carrying capacity of the biosphere to produce enough food for the human population and domesticated animals. The overall effect of climate change on agriculture will depend on the balance of these effects. Assessment of the effects of global climate changes on sustainable agriculture might help to anticipate and adapt farming to maximize agricultural production (Fraser, 2008). Due to climate change, several types of biotic and abiotic stresses are portrayed to confront with the existing life on the earth.

As per the Darwin's concept — survival of the fittest — the surviving lives develop several adaptational changes both phenotypically as well as genetically. Under the phenomenon of adaptation/acclimatization against the changed climate, the living organisms at molecular and biochemical level undergoes various changes to adapt to the new environment. Living organisms can tolerate the adverse effect of a change up to a certain threshold level through alterations in various biochemical molecules which are involved in the proper functioning of the tissue system. The level of biochemical molecules such as enzymes, proteins, amino acids, fat or carbohydrate (reducing sugar) changes; in some it becomes high and in some, it has a lower activity under certain conditions. In response to different stresses, various genes or set of genes get activated which help them to adapt/acclimatize under stress or adverse climate.

It is portrayed that the present changes in climate have restricted the plant growth and productivity. Although in counter defence crop, plants also develop entirely different mechanisms and produce various different biochemical molecules to survive even under the un-favourable climate. Alterations in biochemical traits involve high activity of biochemical molecules such as antioxidants, osmolite, reducing sugars, phenolic compounds, unsaturated fatty acids, NADH oxidase's activity, kinases, etc., On the other hand, the activity of various biochemical molecules lower down as reactive oxygen species (ROS) like H_2O_2 . The biochemical traits such as malondialdehyde (MDA) content, and antioxidant enzymes activities within the flag leaves probably play a key role in enhancing the tolerance capacity of the crops.

Biochemical Traits of Genotypes for Climate-Change Adaptation

Due to adverse climate changes, various catastrophes/environmental stress factors such as elevated temperature, drought, salinity and rise in CO_2 concentration affect the plant growth and pose a growing threat to sustainable agriculture. Climate change has become a hot issue due to concerns about its effects on plant resources, biodiversity and global food security. Plant adaptive strategies to these stresses are coordinated and fine-tuned by adjusting growth, development, and cellular and molecular activities through the regulated expression of biochemical traits such as protein kinases, total antioxidant capacity, photosynthetic efficiency, expression of heat shock proteins (HSPs), alteration in phenolic contents, reactive oxygen species (ROS), hormonal regulation and metabolites profiling (Box 1).

Screening and Evaluation Methodology of Suitable Genotypes

Abiotic stresses are the environmental factors which are directly or sometimes indirectly responsible for the hindrance in the growth and development of plants and ultimately loss in total yield. Breeders are working hard to develop cultivars, which can perform better under the vagaries of nature, but selection of a suitable germplasm of a variety from a pool of thousands of germplasms, is itself a big challenge before them. Even though lot of tools have been developed for screening of different germplasms before using them for breeding, all these tools require enough considerable time as well as resources. Biochemical parameters have been observed to be the most potent tools for screening of germplasms within an acceptable time frame with high accuracy and are easy to execute. Some of the

Box 1

Biochemical Traits of Genotypes for Climate Change Adaptation

- High cell membrane stability
- High structural proteins (in cell wall protein)
- High expression and activities of antioxidant isoenzymes
- Low accumulation of hydrogen peroxide
- Low accumulation of proline
- High accumulation of fructans
- High accumulation of trehalose
- High activity of calmodulin-dependent protein kinases
- High activity of mitogen-activated protein kinase
- High chlorophyll content
- High phenol accumulation
- High grain protein content

biochemical parameters like protein profiling, isoenzymic electrophoretic profiling, antioxidant enzyme activity assay, hydrogen peroxide estimation, total antioxidant capacity, phenol content, proline content and NADH oxidase activity assay can be used for screening of varieties of plants for their tolerance capacity in response to different abiotic stresses before using them in a breeding program.

Reactive Oxygen Species and Antioxidants

Catastrophes/ environmental and biotic stresses are well-known for the production of reactive oxygen species (Foyer and Noctor, 2005). Reactive oxygen species (ROS) control several processes in plants. However, being toxic molecules, they are also capable of injuring the plant cells. The ROS could potentially affect many cellular processes involved in plant/pathogen interactions. The production of ROS is a very important defence mechanism in plants against stresses/

pathogens. However, excessive production of ROS may cause a disruption in cellular functions, leading finally to cell death. The equilibrium between ROS production and scavenging is extremely important. ROS scavenging antioxidant enzymes include superoxide dismutase (SOD), catalase (CAT) and ascorbate peroxidase. Antioxidant enzymes function to eliminate free radicals and are localized to several different sub-cellular compartments within the plant cell. (Jiang and Zhang, 2001) It is believed that the exogenous application of ABA enhances the levels of superoxide radicals and H_2O_2 , followed by increase in the activity of antioxidant enzymes like superoxide dismutase, catalase and ascorbate peroxidase. Antioxidants are compounds that can delay or inhibit the oxidation of lipids or other molecules by inhibiting the initiation or propagation of oxidative chain reactions. The anti-oxidative effect is mainly due to the phenolic components, such as flavonoids, phenolic acids, and phenolic diterpenes. The antioxidant activity of phenolic compounds is largely due to their redox properties, which can play an important role in absorbing and neutralizing free radicals, quenching singlet and triplet oxygen, or decomposing peroxides.

Protein Accumulation in Response to Different Stresses

A plant activates its defence mechanism against different abiotic stresses by enhancing the expression of stress proteins like heat shock proteins, antioxidant enzymes, protein kinases, signalling molecules, etc. Ultimately, the total protein content inside the plant cells increases in response to different stress treatments. Even though the change in protein-content is meagre, it is frequently used to differentiate a normal plant from a stress-challenged plant.

Methods of Protein Estimation

There are several methods for estimation of protein in a plant. These include methods of Lowry, Bradford, bovin serum albumin (BSA), etc. Lowry's method is based on the principle that the phenolic groups of tyrosine and tryptophan residues (amino acid) in a plant protein produce a complex of purple blue colour (having maximum absorption at 660 nm), with Folin-Ciocalteu reagent (which consists of sodium tungsten molybdate and phosphate). Thus, the intensity of color depends on the amount of these aromatic amino acids present and will thus vary for different proteins. In most proteins estimation techniques, Bovin Serum Albumin (BSA) is universally used as a standard protein, because of its

low cost, high purity and ready availability. The method is sensitive down to about $10\text{ }\mu\text{g mL}^{-1}$ and is widely used for protein assays despite its being only a comparative method, and being subject to interference from tris buffer, EDTA, non-ionic and cationic detergents, carbohydrates, lipids and some salts.

The Bradford dye-binding assay is a colorimetric method for estimation of total protein concentration (for experimental procedure, see Box 2). It involves the binding of Coomassie brilliant blue to protein. Unlike many other assays, including the Lowry procedure, the Bradford assay is not susceptible to interference by a wide variety of chemicals present in the samples. The notable exception is high concentrations of detergents. There is a significant protein-to-protein variation in the absorbance values obtained with the Bradford procedure and it is advisable to choose a protein standard that is likely to give absorbance values close to those for the protein samples of interest.

Box 2

Protein Estimation by Bradford Method

1. Pipette 0, 2, 4, 6, 10, 15 and 20 μL of BSA (1 mg/mL) into assigned wells of a 96-well plate.
2. Pipette up to 20 μL of unknown samples into individual wells of a 96-well plate.
3. Add 40 μL of Bradford reagent into all wells containing standard or sample.
4. Add dd H_2O to all wells to bring the final volume to 200 μL .
5. Read absorbance at 595 nm without any prior incubation using multi-well microtiter plate reader.

Hydrogen Peroxide Accumulation against Stresses

For adaptation to various environmental stresses, plants evolve complex regulatory mechanisms. One of the consequences of these stresses is the increase in the cellular concentration of reactive oxygen species (ROS), which are converted subsequently to hydrogen peroxide. An oxidative burst caused by the biotic or abiotic stresses

leads to a disturbance in the cellular redox balance and is highly toxic to plant cells. Recently, H_2O_2 , in addition to being a toxicant, has been regarded as a signalling molecule and a regulator of the expression of some genes in plant cells. These include genes encoding antioxidants, cell rescue/defence proteins, and signalling proteins such as kinase, phosphatase, and transcription factors. Generally, hydrogen peroxide and reactive oxygen species (ROS) exist naturally in an aerobic environment. The major sources of hydrogen peroxide include misfires in the electron transport chains of chloroplasts and mitochondria, the Mehler reaction, a wide variety of limited substrate oxidases, type III peroxidases, and NAD(P)H oxidases. Some of these produce H_2O_2 directly, and others via more reactive intermediates (e.g. $^*\text{O}_2^-$). Broadly, these events are enhanced by stresses, although they occur as an integral part of many facets of plant development.

Hydrogen peroxide is involved in a wide variety of reactions and signalling cascades necessary for all aspects of plant growth and integration of different activities, ranging from the development of individual root hairs to xylem differentiation and lignification, to wall loosening and wall cross-linking, to root/shoot coordination and stomatal control. Accumulation of hydrogen peroxide higher than a certain limit is injurious to the cells, so the plant maintains the internal balance by enhancing the antioxidant activities inside the cells. Hence, there is a need to correlate the accumulation pattern of hydrogen peroxide with the activity of different antioxidant enzymes in order to characterize different germplasms of crops for their abiotic stress tolerance.

Estimation of Hydrogen Peroxide

The concentration of H_2O_2 can be estimated using the method described by Loreto and Velikova (2001) (Box 3).

Superoxide Dismutase and Catalase Activity in Response to Abiotic Stresses

Under different abiotic stresses, plants evolve both enzymatic and non-enzymatic mechanisms to scavenge the rapidly-evolving reactive oxygen species (ROS). Enzymes, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POX), ascorbate peroxidase (APX) and glutathione reductase (GR) (Zhang *et al.* 1995), and non-enzymatic antioxidants such as tocopherols, ascorbic acid, and

Box 3

Estimation of Hydrogen Peroxide

1. Take a leaf sample (0.3 g) and homogenize it in 3 mL of 1% (w/v) trichloroacetic acid (TCA).
2. Centrifuge the homogenates at $10,000 \times g$ (4°C) for 10 min. Add 0.75 mL of the supernatants to 0.75 mL of 10 mM potassium phosphate buffer (pH 7.0) and 1.5 mL of 1 M potassium iodide.
3. H_2O_2 -content of the supernatant can be estimated by comparing of the absorbance values at 390 nm to a standard calibration curve in the range from 10 to 200 nmol/3 mL cuvette.
4. H_2O_2 concentration should be expressed as $\mu\text{mol g}^{-1} \text{fw}$.

glutathione (GSH) act in concert to detoxify ROS. Superoxide dismutase, which is present in all the subcellular portions like mitochondria, chloroplast, microsomes, glyoxosomes and cytosol, forms the first line of defence against active oxygen species. Superoxide dismutases (SODs) are classified into three different types, viz. iron SOD, manganese SOD and copper-zinc SOD. These SODs remove the O_2^- radicals from the compartments where they are formed.

Catalases are tetrameric heme-containing enzymes with the potential to directly dismutate H_2O_2 into H_2O and O_2 and are indispensable for ROS detoxification during the stressed conditions. Catalases have one of the highest turnover rates for all the enzymes. The catalase isozymes, studied extensively in higher plants, have been shown to be regulated temporally and spatially and may respond differentially to light. Antioxidant isoenzymes profile can be used as a tool to characterize different germplasms for their tolerance capacity.

Protocols for Superoxide Dismutase and Catalase Activity Assay

Take leaf materials (1 mg) and ground in 6 mL of ice-cooled 50 mM potassium phosphate buffer (pH 7.0) containing 2 mM sodium-EDTA and 1% (w/v) polyvinylpyrrolidone (PVP). Centrifuge the homogenates at $10,000 \times g$ (4°C) for 10 min. The tissue extracts can be either stored at -78 °C or used immediately for subsequent analyses of superoxide dismutase and catalase. For estimation of

soluble protein content, coomassie blue dye-binding assay can be used (Bradford, 1976). Bovine serum albumin (BSA) should be used for the preparation of the standard curve.

Superoxide dismutase activity can be determined by measuring its ability to inhibit the photochemical reduction of nitro-blue tetrazolium (NBT) in the presence of riboflavin in light (Giannopolitis and Ries, 1977). One unit of enzyme activity is determined as the amount of enzyme needed for inhibition of 50% NBT reduction rate by monitoring absorbance at 560 nm using a spectrophotometer. Activities of catalase enzyme can be measured as described by Chance and Maehly (1955). For assaying catalase activity, the decomposition of H_2O_2 should be followed by a decline in the absorbance at 240 nm. The catalase activity can be determined by following the consumption of H_2O_2 (extinction coefficient, $39.4 \text{ mM}^{-1} \text{ cm}^{-1}$) at 240 nm over a 3-min interval.

Protocols for *In Gel* Activity Assay

Isoenzymic Profiling of Superoxide Dismutase (SOD)

For the isoenzymic study of superoxide dismutase, the protocol of Roychaudhari *et al.* (2003) should be followed.

Box 4

Protocol for Isoenzymic Estimation of Superoxide Dismutase

1. Prepare crude extracts of collected samples in phosphate buffer (pH 7.5) and load 20 μg of proteins (estimated by Bradford method) onto each well of polyacrylamide gel (10%) for native PAGE.
2. Illumination should be discontinued when maximum contrast between achromatic zones and the general blue color is achieved. The gel should be maintained in distilled water till photographed.

Isoenzymic Profiling of Catalase

Isoenzymic pattern of catalase can be detected by the procedure described by Rucinska *et al.* (1999) (Box 5).

Box 5

Experimental Procedure for Isoenzyme Profiling of Catalase

1. Take 20 µg of proteins isolated from collected samples and load it on to Native PAGE gel (10%).
2. Incubate the gel in 3mM H₂O₂ for 10 min and wash it with distill water.
3. Further, incubate the gel in [5 mL of 10% FeCl₃ + 5 mL of 10% K₃Fe(CN)₆ and make up the volume to 50 mL].
4. White color bands will be appeared against blue/greenish background.

Ascorbate Peroxidase Enzyme Activity Assay in Response to Stresses

Ascorbate peroxidase (APX) is believed to play the most essential role in scavenging reactive oxygen species (ROS) and protecting cells in higher plants, algae, euglena and other organisms. Ascorbate peroxidase is involved in scavenging of H₂O₂ in water-water and ASH-GSH cycles and utilizes ASH as the electron donor. The ascorbate peroxidase family consists of at least five different isoforms, including thylakoid (tAPX) and glyoxisome membrane (gmAPX) forms, as well as chloroplast stromal soluble form (sAPX), and cytosolic form (cAPX). APX has a higher affinity for H₂O₂ than catalase and peroxidase (mM range) have and it plays a more crucial role in the management of reactive oxygen species during stress conditions.

APX Isoenzymes Pattern Analysis

Isoenzymes of APX are detected by the procedure described by Mittler and Zilinskas (1994) (Box 6).

Total Antioxidant Enzyme Capacity

Antioxidant enzyme capacity assays can be broadly classified as electron transfer (ET) and hydrogen atom transfer (HAT) based assays. The majorities of HAT assays are based on kinetics, and involve a competitive reaction scheme in which antioxidant and substrate compete for peroxyl radicals thermally generated through the decomposition of azo compounds. Electron transfer based assays measure the capacity of an antioxidant in the reduction of an oxidant, which

Box 6

Analysis of APX Isoenzymes Pattern

1. Prepare enzyme extract for APX by freezing 1 gram of germinated seedling in liquid nitrogen to prevent proteolytic activity followed by grinding with 5 mL of extraction buffer (0.1M phosphate buffer, pH 7.5, containing 0.5mM EDTA and 1mM ascorbic acid).
2. Pass the crude extract through 4 layers of a cheese cloth.
3. Centrifuge the filtrate for 20 min at 15000g and use the supernatant as an enzyme.
4. Load 15µg of the extracted APX enzyme should be loaded onto the 1D native PAGE.
5. 10% resolving gel should be used along with electrode buffer containing 2mM ascorbate and pre-run of 30 min should be given before loading of samples.
6. Equilibrate the gel with 50 mM sodium phosphate buffer (pH 7.0) containing 2 mM ascorbate for 30 min.
7. Incubate the gel in a solution containing 50 mM sodium phosphate buffer (pH 7.0), 4 mM ascorbate and 2 mM H₂O₂ for 20 min.
8. Wash the gel in the buffer for 10 min and finally submerge in a solution of 50 mM sodium phosphate buffer (pH 7.8) containing 2.45 mM nitrobluetetrazolium (NBT) for 15 min with gentle agitation.
9. After 10 min, 28 mM TEMED should be added into the solution. Achromatic zones of white colour against a bluish background represent APX activity.
10. The gel should be washed with distilled water to remove excess stain and take the photograph.

changes colour when reduced. The electron transfer assays include the ABTS/TEAC, CUPRAC, DPPH, Folin-Ciocalteu and FRAP methods, each using entirely different chromogenic redox reagents with extremely different standard potentials. In CUPRAC (cupric ion reducing antioxidant capacity) method, copper (II)-neocuproine reagent is used as the chromogenic oxidizing agent. This method offers distinct advantages over the other electron transfer based assays, namely the selection of working pH at physiological pH (contrary to the Folin and FRAP methods, which work at alkaline and acidic pHs, respectively), applicability to both hydrophilic and lipophilic antioxidants (unlike Folin and DPPH methods), and completion of redox reactions for the most common flavours (unlike FRAP method). This tool can be used to estimate the total antioxidant capacity rather than analyzing the activity of individual antioxidant enzymes.

Protein Profiling and Western Blotting against Abiotic Stresses

Protein profiling is a potent tool to screen an entirely different germplasm of crops for their abiotic stress tolerance capacity. Cultivars behave like a tolerant because of the expression of some of the important stress proteins like HSPs, antioxidant enzymes, signalling proteins and molecules in response to abiotic stresses at different stages of growth and development. The expression of these proteins is also observed in the case of susceptible cultivars but the quantity is very low, which can be easily observed by protein profiling.

Protein profiling can be readily carried out using first dimension sodium dodecyl sulphate polyacrylamide gel electrophoresis (1D SDS PAGE) following the protocols of Lammeli's. Now-a-days, isoelectric focussing (IEF) profiling or 2D PAGE is also recommended in order to characterize the different proteins present in the germplasm for their tolerance capacity. The expressed stress proteins can be functionally characterized using a tool like Matrix-Assisted Laser Desorption Ionisation Time of Flight (MALDI TOF). The western blot analysis using stress protein specific antibodies is common technique used in the area of proteomics for characterizing qualitative as well as quantitative presence of specific stress protein. A comparison of expression and quantification of these proteins in the entirely different germplasm can be used as a tool for screening. This is a well proven fact that the quantity or expression of stress protein in extremely tolerant cultivars is very high compared to the highly susceptible ones at almost all the stages of growth. So, by estimating the accumulation of distinctly

Box 7

Crude Protein Extraction for PAGE

1. Take 1g of freezed germinated seedlings from different cultivars and crush into powder form in pestle and mortar under liquid nitrogen.
2. Add 5 mL of extraction buffer (100mM Tris-HCl, pH 7.3) in pestle and mortar.
3. Pass the crude extract through 4 layers of a muslin cloth centrifuged at 18,000 rpm for 20 min. The supernatant so obtained can be used for 1D SDS PAGE.

different stress proteins in response to stresses at different stages of growth and development, we can easily predict a variety to be tolerant or susceptible to different abiotic stresses.

Protocols for One Dimensional Sodium Dodecyl Sulphate Polyacrylamide Gel Electrophoresis (1D SDS PAGE)

Protein Profiling in Response to Abiotic Stresses

Crude extracts from different germplasm can be used for the one dimensional sodium dodecyl sulphate polyacrylamide gel electrophoresis (1D SDS PAGE) using the method of Lammeli (1970) with some modifications (Box 8).

Box 8

Protein Profiling by 1 D SDS PAGE

1. Estimate the protein of the crude extract using Bradford method (Bradford, 1976) and load equal amount of protein onto each well.
2. Run the sample along with mid-range protein markers. The PAGE run should be carried out at 50 V for 5 hours.
3. Stain the polyacrylamide gel using CBB R250 for 2 hour and the de-staining should be carried out using glacial acetic acid: methanol: water in the ratio of 3:6:51. Silver staining can be also carried out.

Protocols for Western Blotting

The protocols for western blotting are described below:

1. Ground the samples collected at different developmental stages to fine powder under liquid nitrogen.
2. Transfer the powder immediately to a 10-mL tube containing extraction buffer [50 mM phosphate, pH 7.0, 0.2% (v/v) Triton-X-100, 7mM β -mercaptoethanol and 5 mM ascorbic acid].
3. Centrifuge the homogenate at 12,000 rpm for 15 min at 4 °C and transfer the supernatant to a fresh tube and incubate at 100 °C for 10 min and keep the tube under ice for 5 min.
4. Centrifuge the supernatant at 12,000 rpm for 15 min and transfer 50–100 μ L of supernatant to new tubes for direct use or storage at –80 °C.
5. Determine the concentrations of stress stable proteins following Bradford protocol.
6. SDS–PAGE should be performed with a discontinuous buffer system, as described by Lammeli.
7. Denature the protein samples in 1 $\times$ SDS gel-loading buffer by heating at 95 °C for 5 min before loaded into the gel.
8. Separate 15 μ g of protein samples electrophoretically on low range SDS–PAGE and transfer onto polyvinylidene fluoride (PVDF) microporous membranes using the semi dry blotter.
9. Carry out the western blotting procedures as suggested by Mazhar and Basha using anti-stress protein specific antibody and mice anti-rabbit IgG antibody conjugated with alkaline phosphatase. Fresh-developing buffer (100 μ L of nitro blue tetrazolium (NBT) solution and 100 μ L of BCIP solution in 10 mL of alkaline phosphatase buffer) can be used for membrane staining, and the reaction can be stopped by washing the membrane in double-distilled water.

Cell Wall Protein (CWP) Profiling against Stresses

The plant extracellular matrix contains typical polysaccharides such as cellulose, hemicellulose and pectins that interact to form dense interwoven networks. Plant cell walls play crucial roles during development and constitute the first barrier of defence against biotic and abiotic stresses. Around 400 cell wall proteins (CWPs) of *Arabidopsis*, representing about one-fourth of its estimated cell wall protein,

have been characterized. Cell wall proteins such as proteases, polysaccharide hydrolytic enzymes, and lipases may contribute to the generation of signals. Recently, the characterization of post-translational modifications such as N- and O-glycosylations has improved our knowledge about cell wall protein structure. The presence of many glycoside hydrolases and proteases suggests a complex regulation of cell wall proteins involving various types of post-translational events. There is a need to extract and identify cell wall proteins and study the change in the structure in response to different abiotic stresses so that the data generated can be used as primary data for screening different genotypes.

Cell Membrane Stability-Indicator of Abiotic Stress

Cell membrane stability can be used as one of the tools for screening different germplasms of a plant for its thermo-tolerance capacity (Blum *et al.*, 1981). Heat stress causes abrupt production of active oxygen species and also causes cellular membrane disruptions, which lead to changes in the lipid composition of the membrane. Cellular membrane disruption leads to electrolyte leakage from heat-stressed tissues and influence the solute-retaining capacity of the plasmalemma. The cell membrane stability measures the electrolyte leakage from the heat-stressed tissue, which is measured using conductometric instrument. The protocol of Fokar *et al.* (1998) can be used to estimate the cell membrane stability index of different germplasms of crops. This is one of the simplest and easiest methods used for screening.

Protocols for Membrane Stability Index (MSI)

Cell membrane stability (CMS) can be estimated using the method of Fokar *et al.* (1998) with some modifications (Box 9).

Phenylpropanoid Pathway Associated Enzyme's Activity against Stresses

It has been demonstrated that thermal stress induces the production of phenolic compounds, such as flavonoids and phenylpropanoids. Phenylalanine ammonia-lyase (PAL) is considered to be the principal enzyme of the phenylpropanoid pathway, catalyzing the transformation, by deamination, of L-phenylalanine into trans-cinnamic acid, which is the prime intermediary in the biosynthesis of phenolics. These enzyme increases in activity in response to thermal stress and

Box 9

Protocol for Membrane Stability Index

1. Select samples with similar leaf size at different stages of growth.
2. Rinse 3.5cm long leaf segments with distilled water and place it in a closed tube with 1mL of distilled water.
3. Treat three replicates for each cultivar in a water bath at 52°C for 1 hour (T1), while the controls should be kept at 10 °C (C1).
4. Add 9mL of distilled water to each tube and incubate the tubes at 10 °C for 24 hours.
5. Keep the samples till room temperature is achieved and measure the conductivity of the solution.
6. Autoclave the tubes at 100°C for 15 min (T2, C2) and measure the conductivity again.
7. Cell membrane stability (%) can be calculated as: $[1 - (T1/T2) / 1 - (C1/C2)] \times 100$.

are considered by most authors to be one of the main lines of cell acclimatization against stress in plants. The protocol of Amrhein et al. (1976) can be used to study the activity of PAL. Hence, the activity of this enzyme can be used to differentiate a tolerant germplasm from a susceptible one. Phenols are oxidized by peroxidase (POD) and primarily by the polyphenol oxidase (PPO), this latter enzyme catalyzing the oxidation of the o-diphenols to o-diquinones. The *activity of polyphenol oxidase* can be estimated by the colorimetric method based on the oxidation of pyrogallol. These activities of enzymes increase in response to different types of stresses, both biotic and abiotic. So, the activity of above-mentioned two enzymes can be used as a benchmark for differentiating between tolerant and susceptible ones.

Osmolyte Accumulation against Abiotic Stresses

Proline Accumulation

Proline is a major organic osmolyte that accumulates in a variety of plant species in response to environmental stresses such as drought, salinity, extreme

temperatures, UV radiation and heavy metals. Although, their actual roles in plant osmotolerance remain controversial, proline has fairly positive effects on enzyme and membrane integrity along with versatile adaptive roles in mediating osmotic adjustment in plants grown under stress conditions. While many studies have indicated a fairly positive degree relationship between accumulation of proline and plant stress tolerance, some have argued that the increase in their concentrations under stress is a product of, and not an adaptive response to stress. As not all plant species are capable of natural production or accumulation of these compounds in response to stresses, extensive research has been conducted examining various approaches to introduce them into plants. Genetically-engineered plants containing transgenic for production of proline have thus far faced with the limitation of being unable to produce sufficient amounts of these compounds to ameliorate stress effects. An alternative 'shot-gun' approach of exogenous application of proline to plants under stress conditions, however, has gained some attention. A review of the literature indicates that in many, but not all, plant species such an application leads to significant increases in growth and final crop yield under environmental stresses. All these factors may vary from species to species.

Protocol for Proline Estimation

Proline contents can be determined by the slightly modified method of Bates *et al.* (1973) (Box 10).

Trehalose Accumulation

Trehalose, a non-reducing disaccharide sugar, is present in a wide variety of organisms, including bacteria, fungi, plants and invertebrates. There are five known trehalose biosynthetic pathways. The most widespread is the trehalose OtsA–OtsB pathway which is found in all the prokaryotic and eukaryotic organisms and is the only trehalose biosynthetic pathway found in plants. This pathway begins as trehalose-6-phosphate synthase (TPS) catalyzes the transfer of glucose from UDP-glucose to glucose-6-phosphate (G-6-P) to form trehalose-6-phosphate (T-6-P) and uridine diphosphate (UDP). Subsequently, the T-6-P is dephosphorylated into trehalose by trehalose-6-phosphate phosphatase (TPP).

Trehalose was first identified from the ergot fungus of rye in 1832. In plants, for many years, trehalose was thought to be limited to the resurrection plants,

such as *Selaginella lepidophylla* and *Myrothamnus xabellifolia*. Nevertheless, the lower levels of trehalose in other higher plants render it nearly undetectable. In yeast and microorganisms, trehalose serves not only as a carbohydrate storage molecule but also as a metabolic regulator and protective agent against various abiotic stresses. In plants, the role of trehalose is not yet thoroughly understood. In recent years, studies have confirmed that the expression of trehalose biosynthesis genes confers abiotic stress resistance in several species. Transgenic introduction of the yeast *TPS1* into tomato resulted in higher contents of chlorophyll and starch, and enhanced tolerance against drought, salt and oxidative stresses. Rice plants over-expressing *Escherichia coli* trehalose biosynthetic genes (*otsA* and *otsB*) as a fusion gene have exhibited less photo-oxidative damage and more favourable mineral balance under salt, drought, and low-temperature stress conditions. In tobacco, heterologous expression of *AtTPS1* genes from *Arabidopsis* increased the tolerance to several abiotic stresses, such as drought, dessication, and temperature (Almeida *et al.*, 2005). However, trehalose gene over-expression can produce aberrations in plant growth, such as dwarfism, delayed flowering, abnormal root development, and lancet-shaped leaves.

Box 10

Protocol for Proline Estimation

1. Take leaf samples (0.3 g) and ground in 10 mL of 3% sulphosalicylic acid.
2. Centrifuge at $10,000 \times g$ for 10 min. and mix the supernatants (2 mL) with 2 mL of freshly prepared acid-ninhydrin solution (1.25 g of ninhydrin, 30 mL of glacial acetic acid, 20 mL of 6 M ortho-phosphoric acid).
3. Incubate in boiling water for 30 min.
4. After the termination of reactions by transferring the samples on ice, extract the reaction mixtures with 5 mL toluene, vortex for 15 s and leave the tubes undisturbed for at least 20 min at room temperature to allow the separation of toluene and aqueous phases.
5. Collect the toluene phase carefully and take the absorbance values at 520 nm using a spectrophotometer. The concentration of proline can be calculated using a standard curve.

Profiling of Fructans

Generally, plants cannot utilize all the carbon skeletons resulting from photosynthesis. Therefore, they store carbon skeletons as short or long-term reserve carbohydrates. Several pathways that link the generation, utilization, and storage of various carbohydrates dominate in the plant intracellular metabolism. Fructans are recognized as one of the principal stored forms of energy in 15% of the higher plants, and in a wide range of bacteria and fungi. They are believed to be synthesized from the sucrose in the central vacuole of plants.

In dicots, inulin-type fructans accumulate as long-term reserve carbohydrates in the underground storage organs such as roots and tubers. In grasses, graminan, levan, and neokestose-derived fructans mainly act as short-term storage compounds in stems, tiller bases, leaf sheaths, elongating leaf bases, and to a lesser extent in leaf blades and roots. The predominant role of fructans is to bridge the temporal gaps between resource availability and demands. However, they can also fuel rapid regrowth in grasses; regulate osmosis during flower opening (Le Roy *et al.*, 2007), and protect plants against cold and drought stress through membrane stabilization.

Profiling of Lipids in Cell Membranes

The possible role of plant lipids, particularly membrane lipids, in high-temperature susceptibility and tolerance is also an important problem. The degree of unsaturation of acyl residues of glycerolipids determines the physical characteristics of cell membranes. Therefore, it can be postulated that the degree of unsaturation in fatty acid should affect various functions of membrane-bound proteins. Glycerolipids of the thylakoid membrane not only serve as the major constituents of the membrane-forming bilayer but also provide hydrophobic ligands to membranous proteins. They also play an important role in maintaining the photosynthetic electron transport machinery and determining the ability of plants to resist thermal stress (Williams, 1994). But, a remarkable increase in protein/lipid protein/ lipid ratio under acclimatization was observed in the thylakoid (Vigh *et al.* 1990). Lipid profiling can be easily carried out using high performance liquid chromatography (HPLC). Hence, lipid profiling can be used as one of the tools for screening entirely different genotypes of plants for their tolerance against various different abiotic stresses.

Protocols for Lipid Profiling

Modified Bligh and Dyer (1959) protocol is used for lipid extraction from the leaves (Box 11).

Box 11

Protocol for Lipid Profiling

1. Put frozen plant material (snap-frozen in liquid nitrogen and stored at -80°C , put back in liquid nitrogen prior to extraction) in a glass homogenizer
2. Add 3.75 mL of MeOH: CHCl_3 (2:1, v/v) mixture.
3. Add 1mL of 1mM EDTA in 0.15M acetic acid.
4. Homogenize carefully.
5. Transfer to a fresh glass tube with screw cap (cap with Teflon rubber inside).
6. Rinse homogenized with 1.25 mL CHCl_3 ; transfer to the glass tube.
7. To the glass tube, add 1.25 mL of 0.88% (w/v) potassium chloride.
8. Vortex carefully.
9. Centrifuge at 3000 rpm for 2 min.
10. Transfer lipid (CHCl_3) phase (lower phase) with a Pasteur pipette and transfer to a fresh glass tube, store in a freezer at -20°C .

A Direct Acid-Catalyzed Transmethylation protocol

1. Place up to 50 mg tissue in a Teflon-lined screw caps glass tube.
2. Add 1 mL of 2.5% H_2SO_4 (v/v) in methanol (freshly prepared).
3. Heat at 80°C for 1 h.
4. Cool to room temperature.
5. Add 500 μL of pentane, followed by 1.5 mL of 0.9% NaCl (w/v) to extract fatty acid methyl esters (FAME).
6. Shake vigorously and then briefly centrifuge to facilitate phase separation.

7. Transfer some of the upper phases (pentane-containing FAME) to an injection vial. Concentrate with a stream of nitrogen if necessary for GC sensitivity.
8. Run GC with a flame ionization detector (FID) on a polar column.
9. Typical GC conditions - split or splitless mode injection, injector, and flame ionization detector temperature, 250 °C; oven temperature program –160°C for 1 min, 40 °C min⁻¹ to 190 °C, 4 °C min⁻¹ to 230 °C, holding this temperature for 4 min.

Activity of Protein Kinase's in Response to Stresses

Protein kinases are key regulators of the cell function as they have a profound effect on a cell. Activities of protein kinases are highly regulated, and they constitute one of the largest and functionally most diverse gene families. By adding phosphate groups to substrate proteins, they direct the activity, localization and overall functioning of many proteins, and serve to orchestrate the activity of almost all the cellular processes. Kinases play a prominent role in signal transduction and co-ordination of complex functions such as the cell cycle. The stress-activated protein kinase (SAPK) and p38 reactivating kinase pathway take part in signalling in response to physical stress, toxins and inflammatory cytokines. This results in the modification of cellular gene expression. Stress-responsive kinase pathways are structurally similar, but functionally distinct from the mitogen-activated protein kinases (MAPKs). The upstream components and the downstream effects of stimulation of stress-activated protein kinase and p38 pathways are less known. Among the processes modulated by stress-responsive pathways are apoptosis, transformation, development and adaptation to environmental changes.

Calmodulin Dependent Protein Kinases against Stresses

Sessile plants have sophisticated signalling pathways to deal with dramatic environmental changes that may affect their normal growth. Calcium is a universal secondary messenger who responds to these stimuli. The fluctuation in cytosolic Ca²⁺ levels can be sensed by calcium-dependent protein kinases (CDPKs), which will modify the phosphorylation status of substrate proteins. CDPKs mediate biotic and abiotic stress signalling pathways. For example, over-expression of the rice CDPK gene *OsCDPK7* provides cold, salt, and drought tolerance to the transgenic rice plants, demonstrating the potential of CDPK engineering to

generate enhanced stress tolerance in crops. In wheat, 10 out of 14 CDPK genes appeared to respond to abiotic stresses, including drought, NaCl, as well as abscisic acid stimulus. The activity of CDPK enzyme against entirely different abiotic stresses can be used as one of the parameters for screening completely different genotypes for their inherent tolerance capacity.

Mitogen Activated Protein Kinases against Stresses

Mitogen-activated protein kinase cascade is evolutionarily conserved signal transduction module involved in transducing extracellular signals to the nucleus for appropriate cellular adjustment. This cascade consists essentially of three components: (i) MAPK kinase kinase (MAPKKK), (ii) MAPK kinase (MAPKK), and (iii) MAPK connected to each other by the event of phosphorylation. These kinases play diverse roles in intra- and extra-cellular signalling in plants by transferring the information from sensors to responses. Signalling through a MAP kinase cascade can lead to cellular responses, including cell division, differentiation as well as responses to stress. MAPK signalling is associated with hormonal responses. In plants, MAP kinases are represented by multigene families and are involved in the efficient transmission of specific stimuli as well as regulation of the antioxidant defence system in response to stress signalling. Hence, by using molecular tools like quantitative RT-PCR, one can profile the expression of genes of kinases associated with this pathway in entirely different genotypes of crops. Genotypes having remarkably high expression of these genes have an unusually strong defence mechanism against totally different abiotic stresses.

Biochemical Approach for Climate Change Mitigation

In the context of climate change, mitigation has been defined by the UN as 'a human intervention to reduce the sources or enhance the sinks of greenhouse gases'. One of the issues quite often discussed in the context of global climate change is stabilization of green-house gases emission. Various genetically modified crops have been developed where one or other biochemical pathways were manipulated using the tool of genetic engineering to reduce the existing level of GHGs. GM crops like Gm-maize, Gm-cotton, Gm-canola, Gm-soybean, etc. have reduced the total requirement of pesticides and chemicals which was earlier used in the field for protecting the crops from insects and pests and that too, not at the cost of total yield.

Carbon sequestration is one of the approaches in which crops like pigeon pea, green manuring crops, C-4 plants, Azolla trees, etc. can be used for removing carbon dioxide from the atmosphere using biochemical tools like

- Manipulation of Calvin cycle-Enhancing the activity of Rubisco carboxylase enzyme
- Manipulation of C-3 and C-4 photosynthesis
- Manipulation of leaf orientation and crop architecture
- Changing the light saturation point of the plants
- Manipulation of the photorespiration pathway

Plants play two fundamentally different roles as carbon sinks. By capturing atmospheric CO₂ through photosynthesis, plants store large amounts of organic carbon in above and below ground biomass. This is particularly relevant for the perennial trees and herbaceous plants with extensive root systems. Storing carbon in the living biomass represents a rather short-term (decades to centuries) sequestration; when the plants decay, carbon is returned to the atmosphere. However, if they are well maintained or undisturbed, plants in an ecosystem can continue to act as a carbon sink for several centuries. Plant biomass can also be harvested and converted to durable plant products, such as composites and fibre-cement materials, but again, the carbon storage capacity is relatively short-lived. Long-term (millennia) carbon sequestration can be achieved when carbon from above ground biomass transfers to the roots and enters the pool of soil carbon.

Plant as a Sink-enhancing Efficiency

Plants convert atmospheric CO₂ through photosynthesis to sugars, which are transported as sucrose from mature leaves to branches, stems, seeds, and roots for storage, meristematic growth, or cell-wall synthesis; Some of the factors which influence the photosynthetic efficiency are:

- Photosynthetic surface area
- Light interception efficiency
- Solar energy conversion to biomass
- Increasing carbon allocation to roots
- Improving tolerance to biotic and abiotic stresses

By taking care of these factors, one can easily enhance the photosynthetic efficiency of the crops and ultimately it will be easy to use plants as a carbon sink.

In conclusion, phytosequestration is an important aspect of carbon mitigation and it should be viewed as a continuing process, as the strategies and technologies employed will be evolved over time depending on the nature of public and political will, economic incentives, and environmental sustainability projections. There is a need to formulate new research activities to explore the plant genetic engineering as a means to enhance carbon sequestration in above and below ground biomass and soil carbon pools.

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Plant Disease Monitoring for Adaptation Measures under Climate Change Scenario

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Introduction

Abnormal changes in air temperature and rainfall, increased intensity and frequency of storms, drought and flooding and altered hydrological cycle events are the growing concerns for agricultural ecosystems. The global climate change, especially increased levels of CO₂ and temperature (Pachauri and Reisinger, 2007; Watson, 2001), is thought to influence or change all the elements of a disease triangle, viz. host, pathogen and weather factors and their interactions (Legreve and Duveiller, 2010). Both climatic variability and climate change are the relevant drivers of plant disease epidemics and are expected to alter the synchrony between crop phenology and disease or pest patterns. This change in climatic patterns also affects the spatial distribution of agro-ecological zones, habitats, and distribution patterns of plant diseases and pests which can have significant impacts on food production.

Whatever may be the reason, be it climate change, global change or shifts in seasonality, changes in disease situations have already been experienced as some minor diseases have become major diseases in the Indian subcontinent. Current shift in the disease scenario in India, especially in rice and wheat, is a case in point. In rice, bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*) has become a global biotic threat despite constant efforts to improve resistance through exploitation of host *R*-gene. Sheath blight (*Rhizoctonia solani*) and tungro virus that were of minor importance, have emerged as major problems in most of the rice-growing areas. Spot blotch (*Bipolaris sorokiniana*), once unknown or of minor importance, has become a serious problem in wheat. Increasing trend in winter temperature probably provides a favourable situation to the spot blotch in the north-western India (Duveiller *et al.*, 2007). Dry root rot (*Rhizoctonia bataticola*) in

chickpea is becoming more severe in the rainfed environments due to moisture stress and higher temperatures (Pande *et al.*, 2010). Excess moisture on the other hand is favouring some of the dreaded soil-borne diseases caused by *Phytophthora*, *Pythium*, *Rhizoctonia solani* and *Sclerotium rolfsii*, especially in pulses (Sharma *et al.*, 2010).

Quantitative analysis of climate change is largely lacking from field, laboratory or modeling-based assessments. The plant pathologists' should provide long-term as well as short-term climate change adaptation measures to reduce the risk of crop loss due to sudden emergence of diseases so far unknown or economically negligible. Therefore, regular disease monitoring and surveillance is important since disease management does not work like fire fighting. Disease risk in advance requires for short-term or tactical disease management and disease scenario based on climate forecasts are to be the basis of future strategies. Identifying and quantifying the impacts of climate changes on plant diseases is a complex phenomenon (Coakley and Scherm, 1996; Shaw and Osborne, 2011) as there is a great deal of uncertainty about the accurate climate forecast.

There is a need to identify and explain the changes in disease scenario already appeared or likely to be that may help to predict or assess the regional vulnerability due to climate change and may generate information and knowledge to develop adaptation strategies, techniques and methodologies. In this chapter, emphasis has been given on methodologies that can be used for prediction of climate change impact on diseases in order to facilitate tactical and strategic disease management options for sustainable crop production.

Background

For qualitative information, variations in host-pathogen interactions under controlled individual or interactive exposure of CO₂, ozone, radiation, temperature, and rainfall can be monitored through experiments to quantify enhancement or decline in disease development. Changes in epidemic features, namely, primary infection rate, incubation /latent period and basic infection rate, disease progress curve, parameters for resistance and susceptibility enables to explain the impact of elevated exposure level. Various quantitative models, decision support systems and geographic distributions of diseases are being used for the assessment of these changes.

Monitoring of Host-Pathogen Interaction under Controlled Exposure

It is reported that rising concentration of CO₂ may modify pathogen aggressiveness and/ or host susceptibility, affecting initial establishment of the pathogen on the host and increased fecundity and growth of some fungal pathogens (Chakraborty *et al.*, 2000; Matros *et al.*, 2006). In both biotrophs and necrotrophs, significant changes have been reported in the onset and duration of stages in the pathogen life-cycle under the elevated CO₂ levels. Latent period was extended under high CO₂ concentration in all the pathogens studied so far. Together with an increase in plant canopy size, especially in combination with humidity, the increase in abundance and biomass can enlarge the size of pathogen population. However, there is not enough evidence to generalize whether elevated levels of CO₂ and temperature will increase or decrease or will have no effect at all on pathogen. There is a need to study more number of host-pathogen interactions under the elevated exposures of temperature and CO₂.

Modelling Disease Development under Climate Change

Disease development has been modelled using various approaches, including growth curve analysis, analytical models using linked differential equations, and mechanistic simulation models (Madden *et al.*, 2007). However, most of these models ignore canopy-level interactions. Plant canopy occupies a three-dimensional space to capture and utilize solar radiation, atmospheric gases, soil nutrients and water (Chakraborty *et al.*, 2000). Dynamics of the architecture of the plants is crucial in determining the consequences of interactions with the environment. Plant disease, resulting from the host-pathogen interaction in a conducive environment, is manifested in the 3-D space of a plant canopy or root system. Rise in temperature and CO₂ levels might change the architecture of plants and thereby alterations in the pathogen-host interaction. Dynamic simulation of canopy architecture in the elevated and ambient exposure conditions enables the exact quantification of contrasting effect between these levels. Through 3-D, a 'virtual plant' model was created to incorporate the disease development within the canopy structure using L-systems (Wilson *et al.*, 1999) to assess the impact of disease on the modified canopy.

Decision Support System

Crop Growth Linked with Disease Models

Simulation modelling is an effective approach for studying the impact of global and climate changes on crop diseases and can improve quantitative understanding of the dynamics of epidemics or yield loss build-up. These models are also useful for the formulation of strategies, management decisions, research priorities, and analysis of the future scenarios. Luo *et al.* (1997) combined two simulation models, CERES-Rice (rice growth simulation model) and BLASTSIM (rice leaf blast epidemic simulation model) by linking the effects of leaf blast on rice photosynthesis and biomass production based on the experimental data. The effects of weather, nitrogen, water and crop management practices on rice growth were also considered in the model. Biomass production as well as its distribution across different plant parts, was simulated. Similarly, Infocrop as decision support system provides crop growth under non-limiting conditions, and a significant use of such models is in determining the potential yields (Aggarwal *et al.*, 2006). Since potential growth conditions are not featured in the cropping system, additional relationship has to be specified in the model to have an application value. The major limiting factors (e.g., water stress, nitrogen stress, competition from weeds or disease outburst) are then identified and their effects on leaf area development, radiation-use efficiency and partitioning factors are derived and expressed mathematically.

Prediction of Probable Distribution of Diseases under Climate Change Scenario for Long-term Strategic Decisions

There is a need to anticipate invasion risks from both exotic and indigenous pests under climate change scenario (Sturrock *et al.*, 2011). Ecological niche models or species distribution models are powerful tools to predict the future disease epidemics, and provide support for developing strategies against new threats. Ecological niche models predict the potential geographical range of a species based on two types of georeferenced data, biological data describing the species' known distribution (presence and absence), and environmental data which describe the landscape conditions where the species is found. The CLIMEX model has been used for the prediction of potential geographical distribution of Citrus Black Spot (*Guignardia citricarpa*) risk of spread to regions of the world where the disease does not occur (Paul *et al.*, 2005).

Weather-based Monitoring of Diseases Linked to Geographical Information System along with Satellite Data for Crop Information

The geographical information system (GIS) is commonly used to evaluate and model the spatial distribution of plant disease and to analyze the relationships between environmental factors and disease intensity. The GIS technology is being increasingly applied to cover different aspects of plant disease research and management. Such information, when mapped together, creates a powerful tool for monitoring and management. Inclusion of geo-referenced data on crop and socio-economic conditions can add important targeting and impact assessment information. The GIS can exploit these resources in diverse ways, from the perspective of disease resistance discovery and disease monitoring, as well as for risk mapping and epidemiological purposes. Monitoring and forecasting of trans-boundary diseases rely on coordinated international surveillance networks. The GIS provides a platform for data management of disease surveys, integrated analysis of dispersal, and risk assessment.

Future Disease Scenario Generation Based on Climate Forecasts

Assessments of climate and weather influence on crop diseases depend on time and spatial scales. The variations in weather during hours or days can be critical for assessing the weather impact on some diseases, whereas in some cases, the average climate over weeks and months could be the main determinant. The response of a pathogen or insect pest to average environmental variables such as weekly or monthly temperatures can be strongly affected by the amplitudes of daily oscillations in those variables. Long-term trials in UK have shown that air quality and human activity were associated with a shift in prevalence of wheat diseases caused by *Septoria tritici* over *Stagonospora nodorum* over the course of decades (Bearehell *et al.*, 2005).

To assess the effect of climate-change scenarios, crop disease models need climate inputs of the same high temporal and spatial resolution-used for their calibration and parameterization, usually weather records at a daily or hourly temporal resolution and plot- or field-level spatial resolution. However, climate-change assessments are made for large temporal and spatial units, and their reliability decreases in the context of high resolution analyses. There are three main approaches to tackle this problem. Climate inputs may be downscaled to finer resolutions (Semenov and Stratonovitch, 2010) and used as input for the

crop disease models. The increased uncertainty of climate- change scenarios at finer resolution may make it more meaningful to assess average future climate-change impacts over long periods, say 30 years, rather than making transient assessments.

Principles

Variations in the host-pathogen interactions under the controlled individual or interactive exposure of CO₂, ozone, radiation, temperature, and rainfall can be monitored through experiments to quantify enhancement or decline in disease development. Artificial exposures in high CO₂ and temperature levels are expected to modify host, pathogen and their interactions and the change in host-pathogen interaction may be estimated both qualitatively and quantitatively. A change in epidemic features, namely primary infection rate, incubation /latent period and basic infection rate, disease progress curve, and parameters for resistance and susceptibility, helps in explaining the impact of elevated exposure levels. In addition, plant disease, resulting from host-pathogen interaction in a conducive environment, is manifested in the 3-D space of a plant canopy or root system. Rise in CO₂ level and temperature might change the architecture of the plants and thereby may induce alterations in pathogen-host interaction. Dynamic simulation of plant canopy architecture in elevated and ambient exposure conditions enables the exact quantification of contrasting effect between these levels.

The crop growth obeys certain physiological principles. Various growth processes can be quantified in response to the environment by mathematical formulae. By linking equations to each other, a mathematical model can be evolved and for convenience, it can be written as a computer program. Such a quantitative model of crop growth enables predictions about crop growth rates and yields under a variety of environmental and management conditions. It may be used as a tool for the grower to assist in his decisions on management operations. At present, the physiological models are largely used as a research tool, especially as a framework in the analysis of experimental results, and in studying the effect of individual processes on crop growth in relation to the environment.

A model can simulate the typical leaf blast monocycle based on crop growth and weather conditions. The infection cycle of blast is described by subroutines

for spore production, dispersion, deposition, leaf infection, latent period, lesion formation, and lesion development. The relationship between process rates of the components of the infection cycle and environmental factors was determined experimentally and was incorporated into the model. Analytical models are necessary to quantify impacts, examine a range of probable scenarios and evaluate prospective strategies.

The potential geographical range based on two types of georeferenced data, biological data describing the species' known distribution (presence and absence) and meteorological data which describe the landscape conditions where the species is found. Due to plant diseases there are changes in optical properties of the crop canopy, viz. changes in reflection, absorption and transmittance. Electromagnetic spectrum in the visible (400-700 nm), near infra-red (700-1200 nm) and short-wave infra-red (1200-2400 nm) regions is normally used for reflectance measurements to detect infection. Changes in the reflected radiation from the plant canopy occur in wavelengths of visible, near infra-red and short-wave infra-red regions. Due to infection, reflectance is increased in the visible range and decreased in the near infra-red band.

General circulation models (GCMs) for global weather forecast have been developed to assess the impacts of potential global climate change. However, these models do not provide specific weather information at the whole-plant level and thus, provide only the gross estimates of conditions that affect plant and disease development. Simulation approach can scale weather information from the global down to the plant scale.

Requirements

The qualitative as well as quantitative assessment of climate change on diseases requires a multidisciplinary approach. Therefore, high infrastructural facilities like environment control, weather equipments, stress monitoring, and remote sensing devices, software systems along with pathogen detection and quantification tools.

Environment Control Facility — Open top chambers for CO₂ exposure (OTC); Free-air CO₂ enrichment (FACE), temperature gradient chambers/free-air temperature enrichment (FATE) or growth chambers having regulation for temperature and CO₂ concentrations.

Weather Instruments — Automatic weather stations in network with telemetry access system, soil temperature sensors with datalogger, pocket weather kits and thermographic camera for specific canopy condition measurements.

Stress Monitoring — For plant stress monitoring, phenomic facility to monitor plant stress due to pests influence and spectroradiometer for measuring spectral reflectance for stress detection due to pathogen infection.

Software Requirements — Image analysis system and mathematical/statistical softwares for ecological niche models customized simulation softwares like Climex, MaxEnt, ModEco, DIVA-GIS, BIOCLIM and the R package 'dismo' (niche model algorithms). For regional disease monitoring, GIS software (ArcGIS) and GPS sets are required. Sonic digitizer is required to determine the rules of plant morphogenesis and software to model using L systems.

Pathological Investigations — For pathological investigations like detection and quantification of inoculums, spore collection volumetric spore trap and laboratory system with immunodiagnosics, infra-red gas analyzer, spectrophotometer, spadmeter, nanodrop and general and specific chemicals and growth media

Data — High resolution temporal weather data, especially hourly temperature and relative humidity, satellite data for region of interest, past weather data preferably for the 100 years and future climate forecasts for 2020, 2050 and 2080.

Procedures

Basic Data for Assessment of Pathogen Growth under Climate Change

Analytical models are necessary to quantify impacts, examine a range of probable scenarios and evaluate prospective strategies.

The probable impact of temperature rise on diseases can be known by comparing the current and projected temperature conditions at a location with favourable temperature range of diseases. It requires a precise determination of temperature range for a pathogen. It can be established by incubating pathogen at a series of temperatures, ranging from low to high in BOD incubators or growth chambers in culture plates. Germination, germ tube growth, sporulation, infection, incubation period and survival should be recorded at as small intervals as possible to account for small differences during the development period at different temperatures.

Data on temperature related development period and survival can then be used for defining favourable temperature range for a species and calculating thresholds of development and thermal constants.

A pair of observations on temperature and the corresponding development period can be used for determining the threshold of development or lower threshold (LT) as follows:

$$LT = (T_1 \times D_1 - T_2 \times D_2) / (D_1 - D_2)$$

where, T_1 and T_2 are the two temperatures and D_1 and D_2 are the corresponding development periods.

The lower threshold (LT) is the minimum temperature at which pathogen development just starts (Figure 1). Between LT and lower lethal temperature, pathogen remains in a state of inactivity, but resumes activity if it is brought into the favourable temperature range. However, once the temperature reaches the lower lethal, the organism dies.

Likewise, upper threshold is the temperature on a higher side that also results in the cessation of pathogen development. Between upper threshold and lethal temperature, organism remains in a state of inactivity and resumes activity if it is brought into the favourable temperature range. However, if temperature reaches upper lethal, then organism perishes.

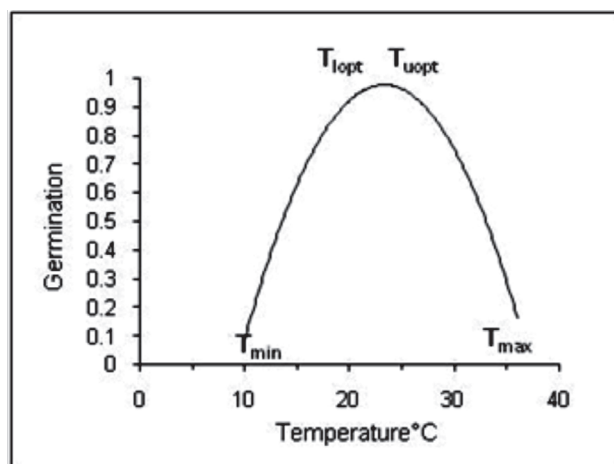


Figure 1. Temperature ranges in relation to pathogen development (T_{min} , T_{lopt} , T_{uopt} and T_{max})

Thermal constant for a particular development stage can be calculated by summing the effective temperatures for the entire period of development of a particular development stage and consequently, the whole life-cycle. Effective temperature is derived by subtracting the threshold of development from the daily average temperature.

Potential Increase in Number of Generations and Population

Information on threshold of development and thermal constant can also be used to determine the impact of climate change on the number of generation and density of a pathogen. Generally, the number of generations per season or year is one of the most important parameters that affect the abundance of a species. Yamamura and Kiritani (1998) have proposed an analytical method to estimate the potential increase in the number of generations under global warming in temperate zones:

$$dN = dT (206.7 + 12.6[m - T_o])/K$$

where, dN = Potential increase in the number of generations a year under global warming; dT = Increase in the annual mean temperature due to global warming; m = Annual mean temperature, °C; T_o = Lower developmental threshold temperature, and K = Thermal constant. In general, assuming a constant temperature rise over the year, species with low T_o and small K are predicted to have an increasing number of annual generations and an earlier appearance of over wintering individual (Yamamura and Kiritani, 1998).

The basic development temperature to calculate the thermal constant can be determined by the hyperbole method (Bean, 1961) using the total development times from the four constant temperatures groups. Thermal constant was obtained from the equation:

$$K = D(T - T_b)$$

where, K = Constant thermal, D = Development time (h), T = Temperature at which the pathogen grew, and T_b = Basic temperature of the pathogen obtained regression programme (Krebs, 1989).

Another approach may be to find out incubation or latent period rate completion rate at different temperature. The rate of incubation period completion was explained with the following model (Figure 2).

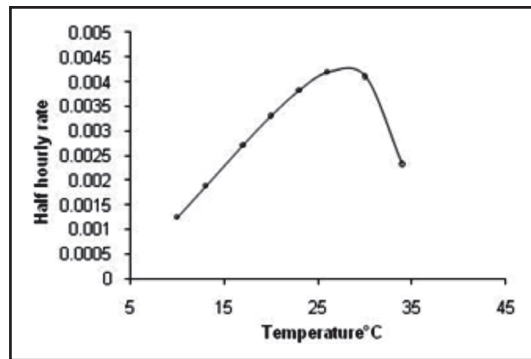


Figure 2. Half-hourly rate in response to temperature

$$\text{Latent period completion rate} = (aT - b) \{ (1 - \exp [c (T - T_{\max})]) \}$$

where, a , b and c are the parameters and $T_{\max}$ is the lethal maximum temperature for the pathogen. Effect of elevated temperature can be estimated in terms of incubation or latent period completion on the pathogen growth on host.

Elevated Carbon dioxide (CO₂) and Ozone (O₃) Effect

Plants Grown under Three Conditions

Open Top Chamber (OTC)

Controlled system (OTC) with elevated level of CO₂ (500-600 ppm) and O₃ up to peak vegetative/reproductive stage and two-to-three levels can be maintained. For control, the plants are to be grown in a controlled system (OTC) with ambient level of CO₂ (350-360 ppm) and O₃ up to peak vegetative/reproductive stage. The effect of CO₂ cannot be interpreted under field or natural conditions as the growing conditions are different.

Free Air CO₂ Enrichment (FACE) System

Elevated level of CO₂ (500-600 ppm) up to peak vegetative/reproductive stage and two-to-three levels can be maintained. For control, the plants can be grown under natural conditions.

Free Air Ozone Enrichment (FAOE) System

Elevated level of O₃ up to peak vegetative/reproductive stage and two-to-three levels can be maintained. For control, the plants can be grown under natural condition.

Elevated Temperature Effect

Temperature Gradient Tunnel

Plants grown under controlled system with elevated level of temperature (gradients of temperature) up to peak vegetative/reproductive stage and at least two-to-three levels can be maintained. For control (ambient level), the plants are grown within chamber but without raised temperature.

Free Air Temperature Enrichment (FATE) System

Elevated level of temperature up to peak vegetative/reproductive stage and two-to-three levels can be maintained. For control, the plants can be grown under natural condition.

Inoculation (standard method) of crop plants with pathogens under favourable conditions (as required by the pathogens) and after establishment of infection plants can be grown in controlled or natural conditions for observations.

Plants are grown under elevated and ambient conditions for sufficient period and after exposure, plants are transported to a glasshouse at ambient conditions and placed inside a dew chamber for period (infection) after inoculation and then in the same glasshouse for 10 days before disease and other assessments are made.

Simulation of Disease under Climate Change

Coupling CERES-Rice and BLASTSIM

The main consideration in coupling the models is that leaf photosynthesis is affected by the blast severity. A quantitative relationship between reduction of photosynthesis and blast severity was used with the following formulae:

$$BL_COEF1 = (1 - DISSEV)^b$$

where, BL_COEF1 is the proportional reduction of photosynthesis as defined by disease, DISSEV is the disease severity (0.0-1.0), and b is a parameter representing the ratio of leaf area occupied by the virtual lesion and by the visual lesion. A value of 3.74 (Bastiaans, 1991) was used in this study. The effect of disease on rice leaf photosynthesis was then calculated using the following equation:

$$CARBO = CARBOB * BL_COEF1$$

where, CARBOB is the daily biomass production (g/plant) calculated in CERES-Rice before modification by blast severity, CARBO is the daily biomass production after modification by blast severity. DISSEV was calculated by diseased leaf area divided by total leaf area:

$$\text{DISSEV} = \text{SIZEOL} / (\text{PLA} - \text{LA_DEAD})$$

where, SIZEOL is the diseased leaf area simulated from BLASTSIM, PLA is the total plant leaf area calculated from CERES-Rice, and LA-DEAD is the dead leaf area estimated by a newly developed subroutine.

Disease severity is generally calculated based on lesion area and living leaf area excluding the dead leaf area. The CERES-Rice model has variables PLA, the total leaf area including those of living and dead leaves, and SENLA, the senescent leaf area of living leaves. In combining the two models, leaf area of dead leaves is estimated to distinguish it from the total senescent leaf area and a relationship can be developed between the proportion of dead leaf area and total senescent leaf area, and degree days after rice sowing (Pinnschmidt, 1989). The following function was developed:

$$Y = 1 - \text{EXP} (-0.2427 - 0.000971(X - 500)) \quad (X > 250) \quad (R^2 = 0.9167)$$

where, Y is the proportion of dead leaf area of total senesced leaf area, and X is the degree days in °C days (sum of average daily temperature minus the base temperature, 8 °C, during the rice growth period). The outputs of the combined model are the area under disease progress curve (AUDPC), daily severity and final estimated yield. The yield loss caused by a leaf blast epidemic was calculated by comparing simulations with and without blast.

For estimating the maximum and minimum relative humidities, needed in BLASTSIM to assess dew formation, it was found that the observed hourly vapours pressure during randomly selected days varied only slightly. It was therefore assumed that vapour pressure during each day remained constant. The maximum and minimum relative humidities during a day are usually at the time when temperatures are minimum and maximum, respectively. The following functions (Goudriaan, 1977) were used to calculate the maximum and minimum relative humidities (MAX_RH and MIN_RH, respectively) based on known daily vapour pressure (VP), minimum temperature (min_temp) and maximum temperature (max_temp) in °C:

$$\text{MAX_RH} = v_p / [6.11 * \text{EXP}(17.47 * \text{min_temp}) / (\text{min_temp} + 239)]$$

$$\text{MIN_RH} = v_p / [6.11 * \text{EXP}(17.47 * \text{min_temp}) / (\text{max_temp} + 239)]$$

Monte-Carlo simulation (Hammersley and Handscombe, 1964) is a modelling technique by which the probability of an uncertain event can be obtained from simulations. The risk of occurrence of significant yield loss caused by severe blast epidemics associated with global climate change may therefore be assessed by simulations. The model can simulate rice blast epidemics driven by weather and rice cultural practice inputs. Estimated yield could be produced by simulations.

Infocrop for Simulation of Disease Effect on Crop Yield under Climate Change

Assessment of crop losses which is a three-step approach taking into consideration disease incidence, damage mechanism and crop yield (Aggarwal *et al.*, 2006). Foliar diseases act as light stealer, assimilation rate reducer as well as tissue consumers. Most important damage mechanisms are coupled to crop growth model at the appropriate plant growth processes level. After quantification and validation of damage mechanisms, crop-disease simulation model can be for climate change impact assessment. Infocrop model can be calibrated by modifying some model parameters such that data simulated by the error-free model fit the observed data. In any instance, even if a model is based on the observed data, simulated values do not exactly comply with the observed data and minor adjustments have to be made for some parameters. Non-compliance may arise from the sampling errors as well as from incomplete knowledge of the system. The model validation stage involves the confirmation that the calibrated model closely represents the real situation.

Simulation of Disease Distribution in Geographic Range under Climate Change Scenario

*Development of Baseline Model to Characterize Suitability of Regional Climates for Facilitating Infection Using CLIMEX Model (Sutherst *et al.*, 2004)*

- Develop climax indices for each location using eco-climatic index Estimation of Eco-climatic Index (EI);

$$\text{EI} = [100/52 \sum (\text{TI}_w \times \text{MI}_w)] \times [(1-\text{CS}/100)(1-\text{HS}/100)(1-\text{DS}/100)(1-\text{WS}/100)]$$

where,

TI_w = Temperature index for week w,

MI_w = Moisture index for week w,

CS = Annual cold stress,

HS = Annual heat stress,

DS = Annual drought stress, and

WS = Annual wet stress.

- For compare locations and EI values are assigned between 0 and 100 (0, unsuitable; 1-10, marginal; 11-25, favourable; and ≥ 26 , highly favourable for establishment

Parameter Estimates Selection Based on the Available Information of Pathogen

Temperature

DV0 (lower limit of growth)

DV1 (lower optimum for growth)

DV2 (upper optimum for growth)

DV3 (upper limit for growth)

Soil moisture

SM0 (lower limit of growth)

SM1 (lower optimum for growth)

SM2 (upper optimum for growth)

SM3 (upper limit for growth)

Cold, heat, dry and wet stress would be adjusted as 0 or values if available.

Field Observation on Disease along with GPS Data and Model Validation

To validate baseline model, overlaid locations of any disease observed and frequencies are to be examined among the suitability classes.

Sensitivity Analysis

Baseline model would be tested to evaluate impact of parameter uncertainty on results. Parameters on temperature and high RH hours on population growth would be adjusted accordingly one by one with constraints $DV0 < DV1 < DV2 < DV3$ and $SM0 < SM1 < SM2 < SM3$.

Weather-based Disease Monitoring using GIS under Seasonal Shift or Abrupt Climate Change

Diseases influenced by the weather factors can be monitored through GIS mapping. Infection is generally favoured during high RH (>80%) hours and favourable temperature for a sufficient period to complete a part of life stage. Therefore, a geographical information system based on weather profiles can be developed following the steps below:

- Development of georeferenced map of a region of interest for temperature and high RH hours and disease occurrence.
- Hourly weather data for the points of interest (www.imd.gov.in) for a specific period or day.
- Disease incidence record for the selected points after one week.

Remote Sensing for Detection and Monitoring of Disease under Climate Change

Due to plant diseases reflectance is increased in the visible and decreased in the near infra-red bands. Wavelength for maximum change in the reflectance is identified and spectral indices or ratio are related with different levels of disease. Once spectral indices are identified, satellite data for corresponding band may be collected and corrected for detection and monitoring of diseases.

Results

A number of parameters for host-pathogen interactions could be estimated for a comparison between elevated exposure and ambient conditions in terms of following:

- **Growth** – Entry number and size of spots (spot blotch)/pustules (rust)
- **Rate of Primary Infection** – Measure of initial infection

- **Sporulation**- Number of spores per 1 sq cm/mL suspension
- **Incubation/latent Period** – Number of days required for 50% spot/pustule development/sporulation. Incubation/latent period models are available.
- **Inoculum Efficiency** – Ratio between spots produced and number of spores applied.
- **Basic Infection Rate** – Number of lesions produced from mother lesions.

In addition to the qualitative information, quantitative support is required for generalization. The pathogens' aggressiveness and /or host resistance can be estimated through population dynamics model (Anderson and May, 1981). The number of infected (X) and non-infected (Y) individuals can be taken to determine the aggressiveness and resistance parameters (α and β) based on following models:

$$dX/dt = (b-d) X + bY - \beta XY$$

$$dY/dt = \beta XY - (d + \alpha) Y$$

$$dN/dt = (b - d) N \alpha Y$$

where, N^* equilibrium population size = $\alpha (\alpha + d) / \beta (\alpha - b + d)$, α and β are the indicators of aggressiveness of the pathogen and host resistance, respectively.

Host level change - probabilities of branching and shoot development rates along the primary and secondary branches; higher secondary and tertiary internode lengths; and reduced axillary bud dormancy of secondary shoots at elevated CO_2 . For host-pathogen interactions, epidemic parameters such as incubation/latent period, infection efficiency and basic infection rates could be estimated for a comparison between elevated exposure and ambient conditions.

Crop Growth Simulation Linked with Blast Model

It could give quantitative information on yield loss (%) and was calculated by comparing the two simulation outputs:

$$YLOS = ((Y_1 - Y_2) / Y_1) \times 100$$

where, YLOS is the percentage of yield loss (%), Y_1 is the simulated yield without blast; Y_2 is the simulated yield with blast epidemics. Thirty simulation runs produced a frequency distribution of yield loss from which the information regarding the risk of yield loss relative to a specific temperature change condition could be obtained.

Case Studies

Impact of Elevated CO₂ Level and Temperature on Host-Parasite Interaction

Chakraborty *et al.* (2000) have studied the effect of elevated level of CO₂ on *Colletotrichum gloeosporioides* and have observed delayed or reduced conidial germination, germ tube growth, and appressorium production when inoculated onto susceptible tropical legume pasture *Stylosanthes scabra*. An extension of the latent period has been reported due to a delay and/or reduction in spore germination and initial establishment in by the pathogen.

Modelling Colletotrichum Gloeosporioides Dynamics within the Plant Canopy under Elevated CO₂ Level

The tropical pasture legume *S. scabra* cv. Fitzroy was grown under ambient (350 ppm) and elevated (700 ppm) CO₂ levels in a controlled-environment facility (CEF) for 13 weeks; plants were digitized weekly using a 3D sonic digitizer to determine the rules of plant morphogenesis and modelled using L-systems by adapting an existing 'Virtual Fitzroy' model (Wilson *et al.*, 1999). Increased probabilities of branching and shoot development rates along the primary and secondary branches; higher secondary and tertiary internode lengths; and reduced axillary bud dormancy of secondary shoots were among the changes at the elevated CO₂ levels. Fitzroy plants at elevated CO₂ level had 35%, 26%, 25% and 44% higher shoot length, node number, leaf area and shoot biomass, respectively, than those at the ambient CO₂ level. The overall effect of elevated CO₂ level on plant height, internode length, number of leaves and growth habit can be clearly seen from the virtual Fitzroy model taken as a snapshot of 97-day old plants.

To sum-up, the elevated CO₂ level increased the leaf area and plant biomass as expected. Induced resistance at elevated CO₂ level was observed from the significant reduction in susceptible- and resistant-type lesions per leaf and infection efficiency as compared to ambient CO₂. Multiple linear regression analysis was used to derive relationships between lesion number and the number of nodes at the primary, secondary and tertiary branch levels, and equations were incorporated in models for ambient and elevated CO₂ levels. As young leaves are more susceptible than the older leaves, the distribution of lesions on primary, secondary and tertiary branches largely reflected the leaf age. This effect was clearly evident from a reduced number of lesions at elevated CO₂ level. Correlation

and regression analyses were used to examine the relationships between anthracnose lesions on plants grown at the elevated and ambient CO₂ levels, weather, and inoculum variables. At both the CO₂ levels, lesion number per plant was positively correlated with the mean hourly relative humidity (MHRH) and negatively correlated with the solar radiation (SOLRAD).

BLASTSIM

Luo *et al.* (1998) simulated the risk of yield losses caused by rice leaf blast associated with temperature changes above and below for five Asian countries. The outputs of the combined model were the area under disease progress curve (AUDPC), daily severity and final estimated yield. The yield loss caused by a leaf blast epidemic was calculated by comparing simulations with and without blast. At most locations, temperature change had significant effects on blast development causing yield loss. In warm humid sub-tropics and humid tropics such as Southern China, Philippines and Thailand, lower temperature led to a higher risk of yield loss, and higher temperature decreased yield losses at some locations in these areas.

Disease Simulator for Plant Growth Model

Knudsen *et al.* (1986) had developed a computer model simulates disease progress over the course of growing season, with time steps of 1 day. Interactions between systems components in the model are represented in Figure 3. Disease severity was expressed as the percentage of leaflets either defoliated or having one or more visible lesions. Plant growth, defined as increase in leaflet number, was modelled as a simple logistic function. Parameters for this function were estimated from a model describing top growth of peanut plants and from field counts of peanut leaflet numbers. Since daily relative humidity and temperature summaries have been and continue to be obtained from many locations for use in the leaf spot advisory system, these weather parameters were chosen to drive the simulation model. Multiple regression method was used to develop a second-degree polynomial function with cutoff points that closely approximated ($r^2=0.97$) the daily leaf spot index. The sum of current and previous days' indices were used as an indication of the favourability of weather conditions for disease increase. In our model, we used a linear function of this sum to estimate the infection rate: R = newly infected leaflets per leaflet with sporulating lesions per day. Slope and intercept values for this function were estimated by running

the simulation model with different parameter values and comparing the model's predictions with disease progress data from epidemics in several years. Parameters were calibrated to minimize sums of squares of residuals (observed minus predicted) and to accurately mimic the patterns of disease increase. Latent period (defined as the time in days from infection of a leaflet until sporulation from that leaflet) and infectious period (duration of spore production) were modelled as distributed delay processes; this method imposes a distribution around the mean developmental time (delay) for latent or infectious periods. Mean latent period was estimated daily as a linear function of minimum temperature during high relative humidity periods.

The latent period has been reported to be temperature-dependent ranges from 10 to 21 days. On this basis, we made a simplifying assumption that the relationship is linear with a latent period of 10 days at 22 °C and 21 days at 19 °C and that latent period is never less than 18 days. The other distributed delay parameters (mean infectious period and number of age classes for latent and infectious periods) were estimated from the published observations and by calibrating the model as previously described. Mean infectious period was assumed to be 8 days. Lesions on infectious leaflets were assumed to become

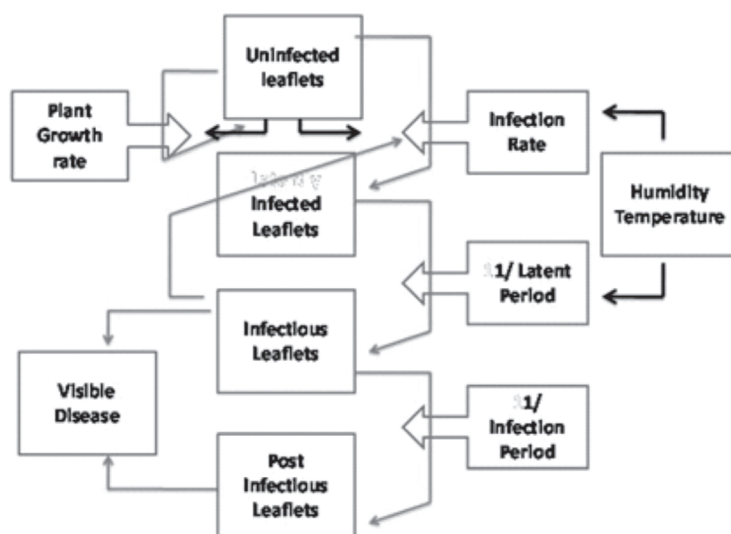


Figure 3. Simulation model for Cercospora leaf spot in peanut

visible at the onset of the infectious period and to remain capable of initiating new infections, under conducive weather conditions, for the duration of the infectious period. Leaflets with post-infectious lesions (including defoliated leaflets) were not a source of inoculum in the model, but were included in the assessment of disease severity.

Variables used in the simulation model are listed in Table 1. Model equations were:

Plant Growth:

$$LFLT_{(t)} = LFLT_{(t-1)} + \{LFLT_{(t-1)} \times 0.1 [(LFMAX - LFLT_{(t-1)}) / LFMAX]\} \quad \dots(1)$$

Disease Progress Curve:

$$INDEX_{(t)} = -1.9 + 0.004 TMP - 1.823 HRH + 0.031 \times [TMP \times HRH] \quad \dots(2)$$

$$(0 < INDEX < 1);$$

$$R_{(t)} = -3.6 + 1.6 [INDEX_{(t)} + INDEX_{(t-1)}]; 0 < R < 1; \quad \dots(3)$$

(linearized function of 2-day index sums)

$$INF_{(t)} = R_{(t)} \times SPL_{(t)} \times CORR; \quad \dots(4)$$

where correction factor $CORR = 1 - \{[LAT_{(t)} + VIS_{(t)}] / LFLT_{(t)}\}$;

(thus, newly-infected leaflets = Rate $\times$ “infectious leaflets” $\times$ proportion leaflets uninfected).

Latently infected leaflets (distributed delay model): for $j = 1$ to KL ; $KL=9$

$$LL_{(j,t)} = LL_{(j,t-1)} + \delta 1_{(j+1,t-1)} - \delta 1_{(j,t-1)} \quad \dots(5)$$

$$\delta 1_{(j,t)} = LL_{(j,t)} \times KL \times P^{-1}, \text{ and } \delta 1_{(KL+1)} = INF \quad \dots(6)$$

$$LAT_{(t)} = \sum_{j=1}^{KS} LL_{(j,t)} \quad \dots(7)$$

(total leaflets with latent infections).

Infectious leaflets (distributed delay model): for $j = 1$ to KS ; $KS = 2$

$$SL_{(j,t)} = SL_{(j,t-1)} + \delta 2_{(j+1,t-1)} - \delta 2_{(j,t-1)} \quad \dots(8)$$

$$\delta 2_{(j,t)} = SL_{(j,t)} \times KS \times i^{-1} \text{ and } \delta 2_{(KS+1,t)} = \delta 1_{(1,t-1)} \quad \dots(9)$$

Table 1. Variables and constants used in the simulation model

Variable	Description
Driving variables	
$HRH_{(t)}$	Daily hours of RH > 95%
$TMP_{(t)}$	Minimum temperature during high RH period
State variables	
$LFLT_{(t)}$	Total number of leaflets
$INF_{(t)}$	Newly infected leaflets daily
$LAT_{(t)}$	Total, latently infected leaflets
$LLU_{(j,t)}$	Latently infected leaflets in the age class j
$SPL_{(t)}$	Total, leaflets with infectious lesions
$SL_{(j,t)}$	Infectious leaflets in the age class j
$VIS_{(t)}$	Total, leaflets with visible leaf spots
$DIS_{(t)}$	Percent disease; $DIS = (VIS/LFLT) \times 100$
Rate variables (units = day⁻¹)	
R	Daily infection rate (newly infected leaflets)
$\delta 1_{(j)}$	Rate of age class change, latently infected leaflets
$\delta 2_{(j)}$	Rate of age class change, infectious leaflets
Auxiliary variables, constants	
$INDEX_{(t)}$	Daily weather index
p	Mean latent period (days)
KL	Index of dispersion around p; $KL = 9$
i	Mean infectious period (days)
KS	Index of dispersion around i; $KS = 2$
$LFMAX$	Maximum number of leaflets (6×10^4 per 10-m row)

Note: ^aParameters i, KL and KS used in simulations were obtained by the curve-fitting procedures described in the text, as was the equation to calculate daily values of R. Other model parameters and equations were obtained from the published literature or experiments, as described in the text.

$$SPL_{(t)} = \sum_{j=1}^{KL} SL(j, t); \quad \dots(10)$$

(total leaflets with infectious lesions).

Visible disease:

$$VIS_{(t+1)} = VIS_{(t)} + \delta 1_{(1,t)} \quad \dots(11)$$

(defoliated or spotted leaflets).

The simulation model can be written in the computer language and can be used for prediction of leaf spot on leaves which is also under the influence of temperature and moisture effects.

Disease Distribution Forecast through Climate Matching

Venette and Cohen (2006) have studied the distribution of *Phytophthora ramorum* infection which has caused extensive mortality to tan oak and several oak species in coastal California. This pathogen has infected at least 72 plant species under natural conditions and 32 additional species in the laboratory. A simulation model was developed using CLIMEX software to evaluate the suitability of the climate in the United States for establishment of *P. ramorum*. CLIMEX was driven by the monthly climate normal data for 1971–2000 collected from more than 5300 weather stations in the contiguous United States. CLIMEX growth-requirement and stress-response parameters were derived from the literature data. Values for the ecoclimatic index (EI), a measure of overall climatic suitability based on temperature and soil moisture, were between 0 and 53. Predictions derived from CLIMEX matched the known occurrences of *P. ramorum* in California and Oregon. Findings of the pathogen were 3.4-times more likely in the areas classified as favourable or highly favourable than in areas classified as marginal or unsuitable. Model results were only modestly sensitive to changes in values assigned to temperature parameters for growth, but were more sensitive to changes in values assigned to moisture parameters for growth. Such information could be used to refine survey and detection programs.

Future Disease Scenario Based on Climate Forecasts

Downscaling methods can be used to forecast epidemic development at a local scale and the same methods can be used to downscale general circulation models (GCMs) used to study the climate change. Salinari *et al.* (2006) have downscaled

two GCMs to simulate future scenarios of downy mildew (*Plasmopara viticola*) epidemics on grape under the climate change. Model runs corresponding to the SRES-A2 emissions scenario, characterized by high projections of both population and greenhouse gas emissions from the present year to 2100, were chosen in order to investigate the impacts of worst-case scenarios, among those currently available from IPCC. Three future decades were simulated (2030, 2050, 2080), using as baseline historical series of meteorological data collected from 1955 to 2001 in Acqui Terme, an important grape-growing area in the north-west of Italy. Both GCMs predicted increase of temperature and decrease of precipitation in this region. The simulations obtained by combining the disease model to the two GCM outputs predicted an increase of the disease pressure in each decade: more severe epidemics were a direct consequence of more favourable temperature conditions during the months of May and June. These negative effects of increasing temperatures more than counterbalanced the effects of precipitation reductions, which alone would have diminished disease pressure. Results suggested that, as adaptation response to future climate change, more attention would have to be paid in the management of early downy mildew infections; two more fungicide sprays would be necessary under the most negative climate scenario, compared with the present management regimes. At the same time, increased knowledge on the effects of climate change on host–pathogen interactions will be necessary to improve the current predictions.

Strategies to Meet the Challenges in Formulation of Adaptation Measures

Maintaining the sustainability of agricultural systems depends directly upon the crop management. In a few decades, the climate change may alter the current scenario of plant diseases and their management. These changes will certainly have effect on crop productivity. Systematic quantitative analysis of these effects will be necessary for developing future disease management plans, such as plant breeding, altered planting date schedules, chemical and biological control methods and increased monitoring of new disease threats. The existing preventive plant protection measures, such as use of diversity of crop species in the cropping systems, adjustment of sowing or planting dates, use of crop cultivars with superior resistance and /or tolerance to diseases and abiotic stress, use of reliable tools to forecast disease epidemics, application of IPM strategies, and effective quarantine systems, may become important in the future. Effective crop protection

technologies are available and will provide appropriate tools to adapt to altered conditions. Therefore, real-time disease monitoring and surveillance have to be in priority to adopt measures against any unforeseen event that might happen due to climate change and /or global change as well as shifts in seasonality.

The adverse effects of atmospheric pollutants may be nullified by improving crop production strategies. However, the impact of changes due to changes in CO₂, temperature and moisture profiles may be more than have been imagined so far. Evidences suggest that climate change has led to extreme weather conditions such as heat waves, record high temperature and in many regions, heavy rainfall in the past 50 years (IPCC, 2012). For abnormal weather or shift in seasonality, crop management practices could be adopted based on the situation that arises. Weather-based disease monitoring, inoculum monitoring especially for soil-borne diseases and rapid diagnostics would play significant roles in the adaptation measures. Effective crop protection technologies are available and expected to cater needs for adaptation. Under the current scenario, disease monitoring and surveillance past, prevailing and future weather data vis-a-vis inoculum information in different pathosystems/agroecosystems would be the critical inputs to assess/identify or /explain local and /or regional risk of probable epidemics under current uncertainties of future climate scenario.

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Selection of Genotypes of Vegetables for Climate Change Adaptation

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Introduction

Vegetables play a crucial role in ensuring food and nutritional security, but they are highly perishable and their prices rise fast under situations like during droughts or floods, putting them out of reach of the poor. Climate change may have more effect on small and marginal farmers, particularly who are mainly dependent on vegetables (FAO, 2009). Moreover, the winter season vegetables are more sensitive to harsh weather than the summer season vegetables. Abiotic stresses like extreme temperatures (low/high), soil salinity, droughts and floods are detrimental to vegetable production. Thus, high temperatures and limited soil moisture are the major causes of low yields in vegetables. The different development phases like vegetative growth, flowering and fruiting are significantly influenced by the vagaries of climate. The effects of elevated temperature and unpredictable and irregular precipitation can disrupt the normal growth and development of plants which ultimately affects crop productivity.

Environmental stresses severely affect the soil organic matter decomposition, nutrient recycling and nutrient and water availability to the plant. However, the intensity and duration of environmental extremes determine the magnitude of impact on crop growth cycle, biomass accumulation and ultimately, the economic return. Crop yields in Asia are expected to decline by 2.5-10% from 2020 onwards and by 5-30% after 2050, with worst declines in South and Central Asia (Cruz *et al.*, 2007). To mitigate the possible impact of climatic change on vegetable production as well as on national economy, several initiatives have been undertaken. These include selection of better adaptable genotypes, genetic manipulation to overcome extreme climatic stresses, measures to improve water

and nutrient-use efficiency and biological nitrogen fixation as well as exploiting the beneficial effects of CO₂ enhancement on crop growth. In this chapter, the impact of global climate change on vegetable crop growth and yield is discussed and strategies to overcome the harmful consequences are outlined. The effect of climate on different quality aspects of vegetable crops that may occur under the changed climate is reviewed.

Status of Vegetable Production

Vegetables are the cheapest resource of nutrients, especially vitamins and minerals. They provide much higher income per unit area per unit time to farmers than staple crops and generate more employment in the rural areas. The worldwide production of vegetables has doubled over the past quarter century and in terms of value the global trade in vegetables far exceeds that of cereals. World's vegetable acreage is 53.98 million hectares with total production of 1012.52 million tonnes (NHB, 2011). Amongst vegetable crops, tomatoes are the most important crop worldwide and are grown on about 5.2 million hectares (Mha) of land (FAOSTAT, 2010). India is the second largest producer of vegetable in world after China, with total production of 146.56 Mt from 8.50 Mha area (NHB, 2011). Production of vegetables has increased at an annual rate of 9.6% in 2010-11 over 2009-10. The productivity of vegetables has also increased up to 17.3 t ha⁻¹ in 2010-11 from 10.5 t ha⁻¹ in 1991-92. Though more than sixty types of vegetables are grown commercially, of which potato, tomato, cabbage, onion, pepper and brinjal are particularly important vegetables in India. The leading vegetable-producing states in India are West Bengal, Uttar Pradesh, Bihar and Andhra Pradesh (NHB, 2011). Most vegetables prefer mild temperatures, thus productivity is low in the hot and humid areas of India. Vegetables are generally sensitive to environmental extremes, and thus high temperatures and limited soil moisture are the major causes of low yields and will be further magnified by climate change.

Environmental Constraints Limiting Vegetable Productivity

Environmental stress is the primary cause of low production of most of the vegetables worldwide; reducing average yields for most of the major vegetables. Under optimum climatic conditions, the productivity of vegetables is three to four folds higher. Climatic changes will influence the severity of environmental

stress on the vegetable crops. Moreover, increasing temperatures, reduced irrigation-water availability, flooding, and salinity will be the major limiting factors in sustaining and increasing vegetable productivity. Plants may respond similarly to avoid one or more stresses through morphological or biochemical mechanisms (Capiati *et al.*, 2006). Environmental interactions may cause stress response of plants more complex or influence the degree of impact of climate change. Measures to adapt to these climate change-induced stresses are critical for sustainable vegetable production. There is a need to do more research on how vegetable crops are likely to be affected by the increased abiotic stresses as there is a direct potential threat from the climate change. Some of the important environmental stresses which affect vegetable production have been reviewed below.

High Temperature

Heat stress due to increase in temperature is a major agricultural problem in many areas of the world. A constantly high temperature causes an array of morpho-anatomical changes in plant which affect the seed germination, plant growth, flower shedding, pollen viability, gametic fertilization, fruit setting, fruit size, fruit weight, fruit quality etc. These problems can be minimized by improvement in the cultural practices and breeding approaches. There are different types of morphological traits which help in heat tolerance in the conventional breeding approaches, these are:

- Long root length has a good ability to uptake water and nutrients from the soil.
- Short life-span which help to minimize the temperature effect on plant.
- Hairiness which provides partial shade to cell wall and cell membrane and repels sun rays.
- Small size of leaf which resists evaporation due to reduction of stomata.
- Leaf orientation enhances the photosynthetic activity and produces tolerance against heat stress.
- Leaf glossiness and waxiness which repel sunlight.

Vegetative and reproductive processes in tomatoes are strongly modified by temperature alone or in conjunction with other environmental factors (Abdalla and Verkerk, 1968). Heat stress above 35 °C has become a major limiting factor

for seed germination, seedling and vegetative growth, flowering & fruit setting, and ripening in tomato. The reproductive development in tomato was more sensitive to high temperatures than vegetative development. The optimum temperatures for tomato cultivation are between 25 °C and 30 °C during the photoperiod and 20 °C during the dark period. However, only 2-4 °C increase in optimal temperature adversely affected gamete development and inhibited the ability of pollinated flowers into seeded fruits and thus, reduced crops yields (Peet *et al.*, 1997; Firon *et al.*, 2006). High temperatures also interfere with floral bud development due to flower abortion. High temperatures can cause significant losses in tomato productivity due to reduced fruit set, and smaller and lower quality fruits (Stevens and Rudich, 1978). High temperatures in tomato cause bud drop, abnormal flower development, poor pollen production, dehiscence and viability, ovule abortion and poor viability, reduced carbohydrate availability, and other reproductive abnormalities. In addition, significant inhibition of photosynthesis occurs at temperatures above optimum, resulting in considerable loss of potential productivity.

With the improvement through conventional breeding two cultivars possess the desired characters, i.e. heat tolerance and high yielded genes are selected and hybridized for selection of desirable plants from segregating generation. However, molecular and biotechnological strategies can be used for inducing heat tolerance in tomato by using such techniques like genetic engineering for the transfer of heat tolerant gene in plant cell which has all other desirable characters. High temperature tolerance has been genetically engineered in plants mainly by over-expressing the heat shock protein genes or indirectly by altering the levels of heat shock transcription factor proteins. Apart from heat shock proteins, thermo-tolerance has also been altered by elevating the levels of osmolytes, increasing the levels of cell detoxification enzymes and through altering membrane fluidity. It is suggested that HSPs may be directly implicated in thermo-tolerance as agents that minimize damage to cell proteins. Tissue culture technique may be used to develop a plant from the transformed cell. Molecular / genetic marker used to identify the gene in plant cell or in F₂ generation that has tolerance ability against high temperature. Now-a-days, biotechnology is contributing significantly to deeper understanding of heat-tolerant gene and heat tolerance mechanism in tomato plants.

Chilling Tolerance in Tomato

The cultivated tomato genotype (*Solanum lycopersicum*, earlier known as *Lycopersicon esculentum* L.) displays limited growth and development at temperatures under 12 °C (Hu et al., 2006). At temperatures between 0 and 12 °C, plants are damaged by the chilling stress. The severity of damage is proportional to the length of time spent in this temperature range. Due to their sensitivity to cold, commercial cultivated tomatoes are planted in the field at later dates to avoid excessively low temperatures and minimize the risk of chilling damage. Cold-resistant cultivars could be planted earlier in the season, leading to an early harvest. Unlike cultivated tomatoes, wild tomato species such as *S. habrochaites* S. Knapp & D.M. Spooner, *S. chilense* (Dunal) Reiche and *S. peruvianum* L., recover rapidly after exposure to sub-optimal temperatures. These genotypes can be grown at high elevations where temperature remains low, below 10 °C. Wild species have been used for constructing genetic maps and identifying genes of agronomic importance. Through backcrosses and selection assisted by molecular markers, cold-resistant genes from wild species can be bred into cultivated tomato varieties (Goodstal *et al.*, 2005).

Following strategies can be adopted:

- The wild genotypes can be introgressed in cultivated tomatoes by somatic and sexual hybridization as well as by chloroplast exchange. The cultivated tomato (*L. esculentum*) is used as a female in crosses due to inability of *L. esculentum* to fertilize ovules of most of the wild species (unilateral incongruity).
- Evaluate the off spring for chilling tolerance.
- Identify the chromosomal regions which may be associated with chilling tolerance in the wild species.

With development of chilling-tolerant tomato, the tomato cultivating season can be extended and it can be produced round the year. The area of adaptation may get broadened for glass house production, cold-tolerant genotype may reduce the energy consumption in horticulture and may cause a reduction in CO₂ emissions and greenhouse effect on global warming. In general, the cold-tolerant genotypes have earliness, water-use efficiency, adaptability and high yield when grown under suboptimal temperature.

Physiological Traits of Chilling Tolerance in Tomato

- Thin stem, short dense glandular hairs and narrow leaflets (*L. peruvianum*)
- Densely hairy stem, leaves and fruits (*L. hirsutum*), high photosynthetic rate and seedling can survive at 0 °C temperature.
- *L. chilense* can survive on rock as it has a deep root system and can tolerate moisture stress.

Drought Tolerance

Water availability is highly sensitive to climate change and severe water-stress conditions will affect crop productivity, particularly of vegetables. In combination with elevated temperatures, decreased precipitation could cause reduction in availability of irrigation water and increase in evapotranspiration, leading to severe crop water-stress conditions (IPCC, 2001). Vegetables, being succulent products by definition, generally consisting more than 90% water (AVRDC, 1990). Thus, water greatly influences the yield and quality of vegetables; and drought conditions drastically reduce vegetables productivity. Drought-stress causes an increase in solute concentration in the environment (soil), leading to an osmotic flow of water out of plant cells. This leads to an increase in the solute concentration in plant cells, thereby lowering the water potential and disrupting membranes and cell processes such as photosynthesis.

The water requirements of vegetable crop range from about 6 inches of water per season for radishes to 24 inches for tomatoes and watermelons. Precise irrigation requirements can be predicted based on crop water-use and effective precipitation values. Lack of water influences the crop growth in many ways and the effect depends on the severity, duration, and time of stress in relation to the stage of growth. Nearly all vegetable crops are sensitive to drought during two periods: flowering and two-to-three weeks before harvesting.

Leafy Vegetables

Cabbage, lettuce, and spinach are generally planted at or near field capacity. Being shallow rooted, these crops benefit from frequent irrigation throughout the season. As leaf expansion relates closely to water availability, these crops,

especially cabbage and lettuce, are particularly sensitive to drought-stress during the period of head formation through harvest. Overwatering or irregular watering can result in burst heads. Broccoli and cauliflower, although not grown specifically for their leaves, respond to irrigation much as the leafy vegetables do. Broccoli and cauliflower are sensitive to drought-stress at all the stages of growth, responding to drought with reduced growth and premature heading.

Roots, Tuber and Bulb Vegetables

In sweet potatoes, potatoes, carrots, and onions, the yield depends on the production and translocation of carbohydrates from the leaf to the root or bulb. The most sensitive stage of growth generally occurs as these storage organs enlarge. Carrots require an even and abundant supply of water throughout the season. Stress causes small, woody, and poorly flavoured roots. Uneven irrigation can lead to misshapen or split roots in carrots, second growth in potatoes, and early bulbing in onions.

Fruit and Seed Vegetables

Cucumbers, melons, pumpkins and squashes, lima beans, snap beans, peas, peppers, sweet corn, and tomatoes are most sensitive to drought-stress at flowering and as fruits and seeds develop. Fruit-set on these crops can be seriously reduced if water becomes limited. An adequate supply of water during the period of fruit enlargement can reduce the incidence of fruit cracking and blossom-end rot in tomatoes. Irrigation is often reduced as fruit and seed crops mature.

Plant growth stage also influences the susceptibility of crops to drought stress. Irrigation is especially useful when establishing newly seeded or transplanted crops. Irrigation after transplanting can significantly increase the plant survival rate, especially when soil moisture is marginal and the evapotranspiration rate is high. Irrigation can also increase the uniformity of emergence and final stand of seeded crops. For seeded crops, reduce the rate of application and the total amount of water applied to avoid crusting. If crusting is present, use low application rates and small amounts of irrigation water to soften the crust while seedlings are emerging.

Physiological Traits for Screening against Drought/Water Stress

Drought Avoidance Characteristics

The drought avoidance characteristics are:

- High relative water content,
- Low membrane injury index,
- Low epidermal conductance,
- High transpiration efficiency,
- Early vigour/ground cover,
- Fibrous and moderate lateral roots,
- Deeper taproots early in the season.

Drought Tolerance Characteristics

The drought tolerance characteristics are:

- High harvest index,
- High water use efficiency,
- More leaf pubescence,
- Partial closure of stomata,
- Leaf osmotic adjustment.

Salinity

Salinity is also a serious problem that reduces growth and productivity of vegetable crops in many salt-affected areas. It is estimated that about 20% of cultivated lands and 33% of irrigated agricultural lands worldwide are afflicted by high salinity (Szabolcs 1992; Ghassemi *et al.*, 1995; Foolad 2004). In addition, the salinized areas are increasing at a rate of 10% annually; low precipitation, high surface evaporation, weathering of native rocks, irrigation with saline water, and poor cultural practices are the major contributors to the increasing soil salinity. In spite of the physiological cause ion toxicity, water deficit, and/or nutritional imbalance, high salinity in the root area sternly inhibits normal plant growth and development, resulting in reduced crop productivity or total crop failure (Ghassemi *et al.*, 1995).

Young seedlings and plants at anthesis appear to be more sensitive to salinity-stress than at the mature stages (Lutts *et al.*, 1995). Onions are sensitive to saline soils, while cucumbers, eggplants, peppers, beet palak and tomatoes are moderately sensitive. One of the most effective ways to overcome salinity problems is the use of tolerant species and varieties (Yilmaz *et al.*, 2004). The response of plants to increasing salt application may differ significantly among plant species as a function of their genetic tolerance.

Flooding

The cultivation of vegetables starts at commercial level in many areas on the onset of monsoon, but production occurs in both dry and wet seasons. However, production is often limited during the rainy season due to excessive moisture brought about by heavy rains. Most vegetables are highly sensitive to flooding and genetic variation with respect to this character is limited, particularly in tomato and early cauliflower. In general, the damage to vegetables by flooding is due to reduction of oxygen in the root zone, which inhibits aerobic processes. Flooded tomato plants accumulate endogenous ethylene that causes damage to the plants (Drew, 1979). The rapid development of epinastic growth of leaves is a characteristic response of tomatoes to waterlogged conditions and the role of ethylene accumulation has been implicated (Kawase, 1981). The severity of flooding symptoms increases with rising temperatures; rapid wilting and death of tomato plants is usually observed following a short period of flooding at high temperatures (Kuo *et al.*, 1982).

The Need for Adaptation to Climate Change

The impacts of climate change on vegetable production will depend not only on climate, but also on the internal dynamics of agricultural systems, including their ability to adapt to the changes (FAO, 2001). Adoption of effective and efficient measures is required to mitigate the adverse effects of climate change on vegetable production, and particularly on their productivity, quality and yield. Current, and new, technologies being developed through plant stress physiology research can potentially contribute to mitigate threats from the climate change on vegetable production. As most of the farmers in developing countries are smallholders, have fewer options and must rely heavily on resources available in their farms or within their communities. Thus, technologies that are simple, affordable, and

accessible must be disseminated to increase the resilience of farms in less-developed countries. Many institutes have been working on addressing the effect of environmental stress on vegetable production. Germplasms of major vegetable crops, which are tolerant to high temperatures, flooding and drought have been identified and advanced breeding lines are being developed in many institutions. Efforts are also underway to identify nitrogen-use efficient germplasm. In addition, development of production systems geared towards improved water-use efficiency and expected to mitigate the effects of hot and dry conditions in vegetable production systems are the top research and development priorities.

Management Practices for Enhancing Vegetable Production

Various management practices have the potential to raise the yield of vegetables grown under hot and wet conditions. Several technologies have also been developed to alleviate production challenges.

Water Management

Since vegetables contain a very high amount of water and many vegetables are eaten raw, therefore use of quality water remains a major concern. The quality and efficiency of water management determine the yield and quality of vegetable products. Too much or too little water causes abnormal plant growth, predisposes plants to infection by pathogens, and causes nutritional disorders. If water is scarce and supplies are erratic or variable, then timely irrigation and conservation of soil moisture reserves are the most important agronomic interventions to maintain yields during drought stress.

There are several methods of applying irrigation water and the choice depends on the crop, water supply, soil characteristics and topography. Surface irrigation methods are utilized in more than 80% of the world's irrigated lands, yet its field level application efficiency is often 40-50% (Von *et al.*, 2004). To generate income and alleviate poverty of the small farmers, promotion of affordable, small-scale drip irrigation technologies are essential. Drip irrigation minimizes water losses due to run-off and deep percolation and water savings of 50-80% are achieved when compared to most traditional surface irrigation methods. Crop production per unit of water consumed by plant evapo-transpiration is typically increased by 10-50%. Thus, more plants can be irrigated per unit of water by drip irrigation,

and with less labour. The water-use efficiency by chilli pepper was significantly higher in drip irrigation compared to furrow irrigation, with higher efficiencies observed with high delivery rate drip irrigation regimes (AVRDC, 2005). For drought-tolerant crops like watermelon, yield differences between furrow and drip irrigated crops were not significantly different; however, the incidence of *Fusarium* wilt was reduced when a lower drip irrigation rate was used. In general, the use of low-cost drip irrigation is cost-effective, labour-saving, and allows more plants to be grown per unit of water, thereby both saving water and increasing farmers' incomes at the same time.

Cultural Management

Simple, affordable and accessible technologies like, mulching and use of shelters and raised beds help to conserve soil moisture, prevent soil degradation, and protect vegetables from heavy rains, high temperatures, and flooding. The use of organic and inorganic mulches is common in high-value vegetable production systems. These protective coverings help reduce evaporation, moderate soil temperature, reduce soil runoff and erosion, protect fruits from direct contact with soil and minimize weed growth. In addition, the use of organic materials as mulch can help enhance soil fertility, structure and other soil properties. Rice straw is abundant in rice-growing areas and generally recommended for summer tomato production. Polythene and sarkanda (*Saccharum* spp. and *Canna* spp.) can also be used as mulching materials. In the areas where temperatures are high, dark-colour plastic mulch is recommended in combination with rice straw (AVRDC, 1990). Dark colour of plastic mulch prevents sunlight from reaching the soil surface and the rice straw insulates the plastic from direct sunlight thereby preventing the soil temperature rising too high during the day.

During the hot rainy season, vegetables such as tomatoes suffer from yield losses caused by heavy rains. Simple, clear plastic rain shelters prevent waterlogging and rain impact damage on developing fruits, with consequent improvement in tomato yields (Midmore *et al.*, 1992). Fruit cracking and the number of unmarketable fruits are also reduced. Another form of shelter using shade cloth can be used to reduce temperature stress. Planting vegetables in raised beds can ameliorate the effects of flooding during the rainy season (AVRDC, 1979, 1981).

Grafting of Vegetables for Stress Management

Grafting of susceptible plant (scion) on tolerant plant (rootstock) helps to grow plant successfully under stress conditions, especially under salt and drought stress conditions. Grafting of vegetables was originated in East Asia during the 20th century and it has been used primarily to control soil-borne diseases affecting the production of vegetables such as tomato, eggplant, and cucurbits. However, it can provide tolerance to soil-related environmental stresses such as drought, salinity, low soil temperature and flooding if appropriate tolerant rootstocks are used. Grafting of eggplants was started during the 1950s, followed by grafting of cucumbers and tomatoes in the 1960s and 1970s (Edelstein, 2004). Romero *et al.* (1997) reported that melons grafted onto hybrid squash rootstocks were more salt-tolerant than the non-grafted melons. However, tolerance to salt by rootstocks varies greatly among species, such that rootstocks from *Cucurbita* spp. are more tolerant of salt than rootstocks from *Lagenaria siceraria* (Matsubara, 1989). Grafted plants are also able to tolerate low soil temperatures. *Solanum lycopersicum* x *S. habrochaites* rootstocks provide tolerance to low soil temperatures (10 °C to 13 °C) for their grafted tomato scions, while eggplants can be grafted on wild brinjal (*S. integrifolium*) as rootstocks to overcome low temperatures (18 °C to 21 °C).

Most of the vegetables are unable to tolerate excessive soil moisture. Tomatoes in particular are considered to be one of the vegetable crops most sensitive to excess water. Until now, genetic variability for tolerance of excess soil moisture is limited or inadequate to prevent losses. Many accessions of eggplant are highly tolerant to flooding (Midmore *et al.*, 1997), thus, can be grafted to improve the flood tolerance of tomato using eggplant rootstocks which were identified with good grafting compatibility with tomato and high tolerance to excess soil moisture. In addition to protection against flooding, some eggplant genotypes are drought-tolerant and eggplant rootstocks can, therefore, provide protection against limited soil moisture stress.

Use of Heat- and Cold-Tolerant Genotypes

Several heat-tolerant genotypes have been developed in vegetables, particularly in tomato. AVRDC, Taiwan, has made significant contributions to the development of heat-tolerant tomato and Chinese cabbage lines (*Brassica rapa* subsp. *pekinensis* and *chinesensis*) adapted to hot and humid climate. The key to achieving high

yields with heat-tolerant cultivars is the broadening of their genetic base through crosses between heat-tolerant tropical lines and disease-resistant temperate or winter varieties (Opena and Lo, 1981). The heat-tolerant tomato lines were developed using heat-tolerant breeding lines and landraces from the Philippines (viz., VC11-3-1-8, VC 11-2-5, Divisoria-2) and the United States (viz., Tamu Chico III, PI289309) (Opena *et al.*, 1992). However, lower yields in the heat-tolerant lines are still a concern.

More heat-tolerant varieties are required to meet the needs of a changing climate, and these must be able to match the yields of conventional, non-heat-tolerant varieties under non-stress conditions. A wider range of genotypic variation must be explored to identify the additional sources of heat tolerance, for example AVRDC's breeding line, CL5915, has demonstrated high levels of heat ranges from 15% to 30%, while there is complete absence of fruit set in heat-sensitive lines in mean field temperatures of 35 °C. Now, new breeding lines have been developed from CL5915 and other sources that exhibit increased heat tolerance. A CL5915 line is considered best combiners for percentage fruit set and total yield in hybrids developed for heat-tolerance (Metwally *et al.*, 1996). Similarly for cold tolerance, several genotypes have shown very good tolerance like, PI-120256, a primitive tomato from Turkey; LA-1777 (*Solanum habrochaites*) from AVRDC, Taiwan, and *Lycopersicon hirsutum* LA3921 and LA3925, both *Solanum habrochaites* from AVRDC, Taiwan, have also shown chilling tolerance. Similarly, EC-520061 (*Solanum habrochaites*) can set fruits under both high (40 ± 2 °C) and low (10 ± 2 °C) temperatures. These lines can be used for the development of cold tolerance in various background.

The Division of Vegetable Science, Indian Agricultural Research Institute, New Delhi, has developed some varieties of vegetables to mitigate the harmful effect of heat. Tomato varieties Pusa Sadabahar and Pusa Sheetal and one hybrid Pusa Hybrid-1 have been developed. They are tolerant to high and low temperatures. Radish variety, Pusa Chetaki has been developed having better root formation under high temperature regime, i.e. April-August. Similarly carrot variety, Pusa Vrishti can form root at high temperature and high humidity i.e. March-August. Early cauliflower variety, Pusa Meghna has been developed which can form curd at high temperature. These varieties can be used directly for mitigating the effect of high temperatures as well as for future breeding programmes. There is a need

to transfer tomato leaf curl virus (TYLCV) resistance, early and late blight resistance in heat tolerant lines through gene pyramiding using wild relatives i.e. *S. habrochaites* and *S. pimpinellifolium* for their wide adaptability.

Drought Tolerance

Most of the vegetables are sensitive to drought; however brinjal, cowpea, amaranth, and tomato can tolerate drought to a certain extent. Genetic variability for drought tolerance found in the cultivated tomato (*S. lycopersicum*) is limited and inadequate. The best source of resistance is from other species in the genus *Solanum*. Wild accessions of tomato, viz. *S. cheesmanii*, *S. chilense*, *S. lycopersicum*, *S. lycopersicum* var. *cerasiforme*, *S. pennellii*, *S. peruvianum* and *S. pimpinellifolium* possess stress tolerance. *S. chilense* and *S. pennellii* produce small green fruit and have an indeterminate growth habit. *S. chilense* is adapted to desert areas and often found in areas where no other vegetation grows (Rick, 1973; Maldonado *et al.*, 2003). *S. chilense* has finely divided leaves and a well-developed root system (Sanchez-Pena, 1999). It has a longer primary root and more extensive secondary root system than cultivated tomato (O'Connell *et al.*, 2007). Drought tests show that *S. chilense* is five-times more tolerant to wilting than cultivated tomato. *S. pennellii* has the ability to increase its water-use efficiency under drought conditions, unlike the cultivated *S. lycopersicum* (O'Connell *et al.*, 2007). It has thick, round waxy leaves, is known to produce acyl-sugars in its trichomes, and its leaves are able to take up dew (Rick, 1973). Transfer and utilization of genes from these drought-tolerant species will enhance tolerance of tomato cultivars to dry conditions, although wide crosses with *S. pennellii* produce fertile progenies. *S. chilense* is cross-incompatible with *S. lycopersicum* and embryo rescue through tissue culture is required to produce progeny plants.

Salt Tolerance

Conventional breeding programmes have shown very limited success in the improvement of salt tolerance due to the genetic and physiologic complexity of this trait (Flowers, 2004). Success in breeding for salt tolerance requires effective screening methods, existence of genetic variability, and ability to transfer the genes to the species of interest. Screening for salt tolerance in the field is not a recommended practice because of the variable levels of salinity in field soils. Screening should be done in soil-less culture with nutrient solutions of known

salt concentrations (Cuartero and Fernandez-Munoz, 1999). A few vegetables like, beet palak, tomato, etc. can tolerate salt to some extent. Most commercial tomato cultivars are moderately sensitive to increased salinity and only limited variation exists in the cultivated species. Genetic variation for salt tolerance during seed germination in tomato has been identified within the cultivated and wild species. Yildirim and Guvenc (2006) have reported that pepper genotypes Demre, Ilica 250, 11-B-14, Bagci Carliston, Mini Aci Sivri, Yalova Carliston, and Yaglik 28 can be useful as sources of genes to develop pepper cultivars with improved germination under salt-stress. In Tunisia, pepper cultivar 'Beldi' significantly out-yielded than other test cultivars at high salt treatments. *S. esculentum* accession (PI174263) showed that the ability of tomato seed to germinate rapidly under the salt-stress (Foolad and Jones, 1991). The tomato genotypes, LA1579 and LA1606, (*S. pimpinellifolium*) and LA4133 (*S. lycopersicum* var *cerasiforme*) from AVRDC, Taiwan, have shown salt tolerance. Wild tomato species, *S. cheesmani*, *S. peruvianum*, *S. pennellii*, *S. pimpinellifolium*, and *S. habrochaites* are the potential source of salt tolerance (Flowers, 2004; Foolad, 2004; Cuartero *et al.*, 2006). Attempts to transfer quantitative trait loci (QTLs) and elucidate the genetics of salt tolerance have been conducted using populations involving wild species. Elucidation of mechanism of salt tolerance at different growth periods and the introgression of salinity tolerance genes into vegetables would accelerate development of varieties that are able to withstand high or variable levels of salinity compatible with different production environments.

Use of Biotechnological Tools in Stress Management

Use of molecular technologies has revolutionized the process of traditional plant breeding. Combining of new knowledge from genomic research with traditional breeding methods has enhanced our ability to improve crop plants. The use of molecular markers as a selection tool provides the potential for increasing the efficiency of breeding programmes by reducing environmental variability, facilitating earlier selection, and reducing subsequent population sizes for field testing. Molecular markers facilitate efficient introgression of superior alleles from wild species into the breeding programmes and enable the pyramiding of genes controlling quantitative traits; thus, enhancing and accelerating the development of stress-tolerant and higher-yielding cultivars for farmers in developing countries. Several QTLs have been identified to stress tolerance in tomato, i.e. for water-use

efficiency in *S. pennellii* and *S. pimpinellifolium* as source of salt tolerance. Only a few major QTLs account for the majority of phenotypic variation, indicating the potential for marker-assisted selection (MAS) for salt tolerance. Integration of QTL analysis with gene discovery and modelling of genetic networks will facilitate a comprehensive understanding of stress tolerance, permit the development of useful and effective markers for marker-assisted selection, and identify candidate genes for genetic engineering.

Traits to be Recorded in Stress Studies

Morphological Characteristics

- Plant height (cm): Height of plant from substrate surface to the vegetative point. Plant height was generally reduced for the plants that were subjected to heat-shock treatment compared to those not subjected to heat-shock treatment.
- Leaf number, leaf length and leaf area (cm²) with an electronic leaf area type Li-3100 (Licor, NE-USA). Plants not subjected to heat-shock treatment had tendency higher leaf area compared to those subjected to heat-shock treatment at both temperatures regimes.
- Number of branches, number of trusses, number of flowers per truss, number of flowers per plant, flowers drop and fruit set percentage may be recorded every week.
- Leaf fresh and dry weight as well as shoot and root fresh and dry weight.

Floral Parameters

- Days to first flower bud appearance, node at first flower bud appearance, days to first anthesis, 50% anthesis, flowers with exerted stigma and antheridial cone splitting should be recorded.

Pollen Parameters

- Number of produced pollen per flower (NPP)
- Number of released pollen (NRP)
- Percentage of viable released pollen (VP)
- *In-vitro* germination of released pollen (PG)
- Number of pollen grains per field

Physiological Parameters

- Membrane injury index (MII)
- Relative water content (RWC)
- Stomatal conductance
- Chlorophyll content,
- Chlorophyll florescence
- Chlorophyll a/b ratio; Photosynthetic rate

Biochemical Parameters

- Antioxidant content
- β -carotene/total carotene (mg/100g)
- Lycopene (mg/100g)
- Ascorbic acid content (mg/100g)
- Total soluble solids (%)
- Acidity (%)
- Phenolic contents
- Antioxidant enzymes

Growth, Yield and Yield Components Measurement

- Days to flowering: Number of days taken from sowing to at least one flower anthesis.
- Days to maturity: No. of days taken from sowing to at least one fruit ripening
- Fruit setting %: Computed by dividing total fruit number by the total flower number from clusters 2 to 6 on each plant.
- Total number of flowers: Flowers from clusters 2 to 6.
- Five fruits for fruit length, width and weight from clusters 2 to 6 on each plant.
- Fruit length: From stem-end to distal-end to one decimal point (in cm) at maturity from cluster 2 to 6 on each plant.
- Fruit width: Recorded (in cm) as the largest diameter of cross sectioned fruit to one decimal place.

- Fruit weight: It is the average fruit weight per plant in grams calculated by dividing the total fruit weight by total fruit number from clusters 2 to 6 on each plant.
- Yield: It is the total fruit weight in grams of each plant.

Thrust Area

To mitigate the effect of climate change in vegetable crops, following strategies are to be adopted:

- 1) Screening of germplasm of major vegetable crops for stress tolerance (high/low temperature, drought, flood, salinity etc.).
- 2) Development of cold and hot set varieties of tomato with better consumer's acceptance.
- 3) Development of low chill requiring varieties in temperate vegetables like cabbage, carrot, beet root, turnip, knol-khol, brussel sprout, etc.
- 4) Development of leafy vegetables like palak, spinach, coriander, etc. with wider adaptability and greater tolerance to high temperature.
- 5) There is also need to increase 'N'-use efficiency and water-use efficiency of vegetable crops through better production system and development of 'N'-use and water use efficient genotypes.

A sustainable programme has been made during the past decade for breeding of tomato, radish, cauliflower, carrot that is tolerant to high temperature and produce satisfactory yields. As greater resistance to insect and disease attack is bred into the heat-tolerant varieties, higher and more stable yields no doubt will be obtained in the years ahead. Thus, there is enough scope for breeding varieties of many vegetable crops better adapted to the high temperature and more resistant to attack by insect and diseases.

Conclusion

A holistic approach is required to overcome stress tolerance rather than a single method. A systems approach, where all available options are considered in an integrated manner, will be the most effective and ultimately the most sustainable measure under a variable climate. For this to succeed, adequate and long-term funding is necessary, scientific results have to be delivered, best approaches utilized and

effective methods sustained to deliver global public goods for impact involving public and private sector together. For reducing malnutrition and alleviating poverty in developing countries through improved production and consumption of safe vegetables will involve adaptation of current vegetable systems to the potential impact of climate change. Vegetable germplasm with tolerance to drought, high temperatures and other environmental stresses, and ability to maintain yield in marginal soils must be identified to serve as sources of these traits for both public and private vegetable breeding programmes. These germplasms will include both cultivated and wild accessions possessing genetic variation unavailable in current, widely-grown cultivars. Genetic populations are being developed to introgress and identify genes conferring tolerance to stresses and at the same time generate tools for gene isolation, characterization, and genetic engineering. Furthermore, agronomic practices that conserve water and protect vegetable crops from sub-optimal environmental conditions must be continuously enhanced and made easily accessible to farmers in the developing world. An effective extension strategy must be in place that includes technical, socio-economic, and political considerations. Finally, capacity building and education are the key components of a sustainable adaptation strategy to climate change.

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Adaptation and Mitigation of Climate Change with Conservation Agriculture

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The report of Intergovernmental Panel on Climate Change (IPCC, 2007) has provided a strong evidence of global climate change and projected that the average global temperature of the atmosphere above the earth's surface would rise by 1.4-4.8 °C by the end of this century. For the Indian region (South Asia), the IPCC has projected the rise in temperature to be 0.5-1.2 °C by 2020, 0.88-3.16 °C by 2050 and 1.56-5.44 °C by 2080, depending upon the scenario of future development. Overall, the temperature increase is likely to be much higher during the winter (*rabi*) seasons than rainy (*kharif*) seasons. Precipitation is likely to increase by 15-40% by the end of the century in all time slices and in all months, except during December-February when it is likely to decrease. The simulations also indicate that there will be an overall increase in the highest one-day rainfall over a major part of the country. In fact, such events have been demonstrative in recent years in several parts of India.

Climate change poses serious threats to productivity and sustainability of the rice-wheat and other cereals-based cropping systems, the backbone of food security of South Asia. Conservation agriculture involving continuous minimum mechanical soil disturbance, permanent organic soil cover with crop residues or cover crops and diversified, efficient and economical viable crop rotations provides opportunities for savings on inputs, improving resource-use efficiency and mitigating greenhouse gas (GHG) emissions and climate change adaptation. Recent research efforts have attempted to develop conservation agriculture (CA)-based crop management technologies, which are more resource-efficient, need less inputs, improve production and income, and reduce GHG emissions compared to the conventional practices (Pathak *et al.*, 2011). The CA-based crop management technologies include zero tillage (ZT) with residues recycling, laser-assisted precision land levelling, direct drilling into the residues, direct seeding of

rice, brown manuring with *Sesbania*, unpuddled mechanical transplantation of rice, raised bed planting, crop diversification, and associated component technologies like site-specific nutrient management, etc. These technologies are being increasingly adopted by farmers in the rice-wheat belt of the Indo-Gangetic Plains (IGP) of India because of the advantages in terms of saving of labour, water, fuel, and cost along with timeliness in operations/practices, particularly for early planting of wheat. These technologies have pronounced effects in rice-wheat system on mitigation of GHG emissions and adaptation to climate change. It has been shown that global warming potential (GWP) is reduced in direct drill-seeded rice and wheat on beds or with ZT compared to the conventionally puddle transplanted rice and tilled wheat. Yields of rice and wheat under heat and water-stressed environments can also be raised significantly by adopting CA-based technologies, which minimize unfavourable environmental impacts, especially in small and medium-scale farms.

The CA-based technologies such as zero or minimum tillage with direct seeding, permanent or semi-permanent residue cover, and crop rotations with sod crops (i.e., forages) have potential for improving the use-efficiency of natural resources, including water, air, fossil fuels, soils, inputs and human resources. Among other things, the efficiencies gained include less land and time to produce the required staple cereals, allowing farmers to diversify crops and cropping patterns or pursue other gainful activities. These technologies can improve the sustainability of the cropping system by conserving the resource base and increasing the input-use efficiency.

The CA-practices are widely adopted in tropics/sub-tropics and temperate regions of the world for both rain-fed and irrigated eco-systems. The acreage of CA is increasing steadily worldwide to cover about 124 M ha (Friedrick *et al.*, 2011, unpublished) land (8% of the world arable land area). Recent estimates have revealed that CA-based resource conserving technologies (RCTs) are being practised over nearly 3.9 Mha of South Asia (Jat *et al.*, 2011). Several studies conducted across the production systems under varied ecologies of South Asia have revealed potential benefits of CA-based crop management technologies on resource conservation, use-efficiency of external inputs, yield enhancement, soil health improvement, and adaptation to changing climates (Gupta *et al.*, 2003; Malik *et al.*, 2005; Gupta and Seth, 2007; Gupta and Sayre, 2007; Gupta *et al.*, 2010; Jat *et al.*, 2010).

Zero Tillage

Zero-tillage is gaining popularity amongst the farmers in the Indo-Gangetic Plains for establishing wheat and to some extent in rice and other crops. By using this technology, the rice–wheat farmers can undertake direct drilling of wheat soon after harvesting of rice without any preparatory tillage, so that wheat crop heads and fills grain before the onset of pre-monsoon hot weather. This involves sowing with a specially-designed zero-till seed-cum-fertilizer drill/planter, which has inverted ‘T’-type furrow opener to make a narrow slit in the soil for placing seed and fertilizer. This helps in saving of time, energy (fuel) and cost by Rs 3000/- per ha. The leaves of wheat do not turn yellow after first irrigation, as in the case of a tilled crop. Further, there is less weed-infestation and the crop does not lodge at maturity. Continuous adoption of zero-tillage has reduced the infestation of *Phalaris minor* in wheat to a large extent, and has helped the farmers to overcome the problem of isoproturon resistance in Haryana. This reduces the herbicide load and cuts down on emissions, as well.



Zero-till seed-cum-fertilizer planter
(Photo courtesy: RWC-IGP, New Delhi)

To practise zero-tillage in a right way, the following steps should be followed:

Checking of machinery: The zero-till drill/planter should be checked before use to ensure that all the parts, viz. openers, fertilizer and seed metering systems, chains, nuts and bolts etc. are in good condition. It should be properly serviced

and maintained, and after use, the fertilizer and seed boxes should be cleaned and moving parts be oiled.

Calibration of drill: Calibration should be done properly at the beginning of the planting season for both seed and fertilizer. Calibration values are sometimes placed on the drill by the manufacturer. Seed metering devices can increase or decrease seed rates within specified limits. To ensure that the drill/planter supplies the correct amount of seed, the calibration should be done as described (Jat *et al.*, 2010) below:

To calibrate to a desired seed rate, first fix seed metering lever in appropriate seed rate delivery notch. Measure circumference of drive wheel (Cd). Measure the width of drill (Wd) or else multiply the number of tynes with distance between two tynes. Put seed material in seed-box and rotate drive wheel manually to ten full rotations and collect seed delivered from each tube separately in polythene bags. Weigh seeds in each bag and also determine the total seed weight (Sw). If the difference in seed weight between individual delivery tubes is more than 10%, contact a mechanic for doing adjustment or repairing of the drill. Repeat operations with fertilizers in box to find weight of fertilizer material (Fw), delivered in 10 full rotations of the drive wheel as described. Calculate seed and fertilizer application rate per hectare using formula (1):

$$\text{Seed rate (kg ha}^{-1}\text{)} = [\text{Sw} / (\text{Cd} \times \text{Wd})] \quad \dots(1)$$

where,

Sw (or Fw) = Total weight (g) of the seed or fertilizers released in 10 revolutions

Cd = Circumference of drive wheel (m)

Wd= Width of the drill (m)

Fertilizer rate (kg ha⁻¹) can be determined using the same formula by substituting the total weight of fertilizer released in grams (Fw) in place of total weight of seed (Sw).

It is cautioned that calculated seed and fertilizer rates can differ by 5% from the actual rates due to drag and slippage of the drive wheel, depending upon the soil moisture, surface roughness, presence of crop residues and field level. Carry out minor adjustments in seed/ fertilizer rates by testing the drill in the field.

Adjustments of drill: The three-point hitch adjustments where the drill fixes to the tractor should be adjusted. The drill should be levelled from side to side and have just enough forward and backward adjustment to enter into the soil at the proper angle. The forward and backward level can be adjusted using the top-link, whereas for adjusting the level on both sides, the hitch lever should be used. Do not adjust the drill too steep or too shallow as planting will be too deep or seeds may drop on the surface, respectively.

Soil moisture at tillage: Do not use zero-till drill when the soil is too wet or too dry. In zero-tillage, drilling should be done at relatively high soil moisture compared to conventional tillage to achieve twin benefits of advancing planting and ensuring a good crop establishment. This additional moisture reduces the soil strength, ensures proper seed-soil contact and helps the emerging roots to penetrate soil easily. However, too wet soil results in more clods formation on drying of soil, and causes aeration stress and root rot. The field should be irrigated soon after planting with zero-till drill to facilitate root penetration in sandy soil.

Cultivar: Crop varieties that have vigorous early growth and tillering are good for zero-tillage. If no recommended variety for zero-tillage is available, the variety that performs well under the conventional planting can be used.

Seed rate: The seed rate for zero-tillage is relatively less than conventional tillage (broadcast seeding); for example, in wheat under conventional till broadcasting farmers use 150 kg ha^{-1} , but with zero-tillage 100 kg ha^{-1} is sufficient. If seed rate is more, the plants will be spindly and may lodge, resulting in low yields. However, wheat can compensate for low seed rate by tillering and adjusting head size and grains per head. It is often recommended to use a relatively higher seed rate (120 kg ha^{-1}) with zero-till seed drill to account for losses in germination because of possible inadequate seed-soil contact and damage by birds of seeds lying on the surface.

Seed germination and sowing: The seed rate for sowing is based on seed germination. While calibrating the drill seed, germination percentage should be considered and seed rate should be adjusted accordingly. For example, if seed germination is 50%, seed requirement for sowing gets doubled. However, the seed lots with less than 95% germination should be avoided. To check germination, place 100 seeds onto a wet newspaper, roll it up and carefully close the ends.

Keep the roll moist and at moderate temperature for 3-5 days. Open the roll and count the number of seeds that have germinated to calculate germination percentage.

Fertilizer mixing and use: Once the drill/planter is calibrated for fertilizer, fertilizer should be placed in fertilizer box. Diammonium phosphate (DAP) or NPK complex should be applied at sowing and urea at the first and second irrigations by top-dressing. Do not leave fertilizer in the box for long, which may lead to formation of cakes and prevents free flow of fertilizer granules to the ground. In surface residue conditions, put more N as basal and urea is the only source.

Irrigation: The time of first irrigation depends on the soil moisture at planting and soil texture and surface residues. Light-texture soils should be irrigated earlier to ensure good rooting and subsequent tillering. However, under zero-till condition with surface residues, the first irrigation in wheat can be delayed compared to conventional tillage.

Weed control: Weed population, especially *Phalaris minor*, is lower in zero-tilled wheat fields compared to ploughed ones. However, if weed population is more than the threshold level, proper weed control measures should be adopted. Apply glyphosate or paraquat at 1.0 kg ha^{-1} (Das, 2008) before sowing of wheat (pre-sowing treatment), if there are already previously-growing weeds in the field. In the standing crop of wheat, clodinafop-propargyl at 0.06 kg ha^{-1} should be followed by or tank-mixed with carfentrazone-ethyl 0.03 kg ha^{-1} , or metsulfuron-methyl 0.005 kg ha^{-1} (Yaduraju and Das, 2002) at post-emergence 30 days after sowing (DAS), depending on the spectrum of weed infestation. Sequential/followed-by application is more safe and efficient than a tank-mix application. In sequential applications, it is better to use grass killer herbicide, viz. clodinafop-propargyl first, followed by the broad-leaved weed killer herbicides, namely, carfentrazone-ethyl, metsulfuron-methyl, or 2,4-D (at 0.5 kg ha^{-1}) after 3-4 days of application of the grass killer herbicides. Sulfosulfuron having a more balanced/broad-spectrum activity on annual grass and broad-leaved weeds, may substitute the tank-mix or sequential application of two herbicides (Das and Kulshrestha, 2002). This with a dose of 0.030 kg ha^{-1} may be recommended exclusively in the areas where resistance to isoproturon and cross-resistance to clodinafop-propargyl has cropped up in *Phalaris minor* populations.

New machines: New variants of zero-till seed-cum-fertilizer drill/planter have been developed to suit the varying conditions and requirements. Happy seeder/turbo seeder has been developed for direct drilling of crops in surface residue (loose and anchored) conditions. It has rotating blades/flaies on the rotor in front of the tynes/openers which cut/shred the residues ahead of the furrow openers and spread over the sown area behind the seed-cum-fertilizer drill. This drill/planter can seed in the surface residues load up to 10 t ha⁻¹. Similarly, there are other planters such as rotary-disc drill for direct drilling in residue conditions. The rotary discs cut the residues and place the seeds and fertilizer in the narrow slit. Farmers often burn the crop residues, particularly of rice, in the north-western Gangetic Plains, which results in pollution in the environment and loss of nutrients and moisture from the surface soil. These machines are very useful for conserving moisture and nutrients and controlling weeds as well as moderating soil temperature. Results of farmers participatory field trials across Indo-Gangetic Plains have revealed that zero tillage helps in timely sowing, and the terminal heat effects are less in zero tillage (~ 65 kg ha⁻¹ day⁻¹) compared to conventional till (~ 77 kg ha⁻¹ day⁻¹) even under late planting (after 21 November till 20 December). Zero-till drilling in residues keeps canopy temperatures lower by 1-1.5 °C during grain filling stage (cooling due to transpiration) owing to sustained soil moisture availability to the plants (Jat *et al.*, 2009a).



Happy seeder for sowing in presence of residues
[Photo courtesy: CSISA (CIMMYT-IRRI) , New Delhi]

Bed Planting

Bed planting technology is the growing of crops on the raised beds alternated by furrows for conserving inputs like seed, fertilizer, water, etc. Beds are usually made 0.6-1.0 m apart, and 2-3 rows of crops are sown on the beds and irrigation water is applied in the furrows. Bed planting systems are reported to help in more efficient use of water under rainfed as well as irrigated conditions because of optimum water storage and safe disposal of excess water. The furrow irrigated raised-bed system (FIRBS) of wheat cultivation could provide savings in seed by 25-40%, water by 25-40% and nutrients by 25%, without affecting the grain yield production. Further, the FIRBS technology reduces lodging owing to less physical contact of irrigation water with wheat culms, and vacant spaces in the forms of furrows, facilitating easy air movement (Chauhan *et al.*, 1999; 2001). Wheat suits better under bed planning because it is adapted to close-growing conditions, and has higher potential for tillering and canopy formation (Das and Yaduraju 2011). Plants also show a considerable plasticity in growth. The FIRBS results in higher leaf area, leaf dry weight, plant height and flag leaf area, but lower tiller number than those in flat bed conventional sowing (Das and Yaduraju, 2012). This method of planting also reduces the populations of weeds on the top of beds, probably due to faster drying and lower soil moisture



Bed planting of wheat

(Photo courtesy: ML Jat, CIMMYT India, New Delhi)

compared to furrows, and closer-growing of crop plants. Thus, weed management, which mainly encompasses the furrow places, becomes easier in this method. Bed planting also facilitates crop diversification (Jat *et al.*, 2005). Several other crops such as cotton, pigeon pea, maize, soybean, vegetables, and sugarcane can be sown/planted on beds using this technology.

Following precautions need to be followed for adopting this technology:

- The field should preferably be laser levelled.
- Soil should have enough moisture for proper germination.
- Use narrow wheels of the tractor to avoid compaction on the slopes of the beds (root zone)
- Seed should be placed 4-5 cm on the bed to ensure good germination.
- Soil on the surface of the bed often dries quickly. In that case, keep some residues on the surface or provide an early post-sowing irrigation.
- Irrigation should be applied in such a way that furrows are filled with water up to 3/4th of the height and water should not flow over top of the beds.
- Beds should be made in north-south direction so that all the plants are exposed to adequate sunlight.
- There should be no residues or undecomposed biomass in the field, otherwise these will interfere with the tynes on the beds and hamper proper placement of seed and fertilizer.



Bed planting of pigeon pea
(Photo courtesy: Division of Agronomy
IARI, New Delhi)



Bed planting of cotton
(Photo courtesy: Division of Agronomy
IARI, New Delhi)

Direct-Seeded Rice

Direct dry seeding of rice (DSR) with subsequent aerobic soil conditions avoids water requirement during land preparation and reduces overall water demand. It is a labour, fuel, time, and water-saving technology and provides yield similar to the transplanted rice when weeds are controlled with judicious use of herbicides. The technology does not affect rice quality and can be practised in different ecologies, including upland, medium and lowland, deep water and irrigated areas by large as well as small farmers. With this technology, soil health is maintained or improved and fertilizer- and water-use efficiencies are higher. Therefore, DSR is technically and economically a feasible alternative to conventional puddled transplanted rice.



Direct-seeded rice

(Photo courtesy: Division of Agronomy, IARI, New Delhi)

Planting time: The wet season direct-seeded rice crop should be planted 10-12 days ahead of the historical trends for the onset of monsoon. For example, in western Uttar Pradesh, monsoon sets in on 21-23 June, so the best seeding time for DSR rice in this region is around 10-12 June. This would help in timely establishment of rice crop before rains to reduce seeding mortality due to submergence, make efficient use of rain water and timely planting of succeeding crop of wheat after rice harvest.

Planting technique and seed rate: The field should be prepared well by 2-3 harrowings and cultivations with a tractor followed by a rotavator, if clods are formed in a heavy soil. For cultivars with medium fine grain, seed rate of 20-25 kg ha⁻¹ is optimum for DSR crop. The seeds, primed by treating with bavistin or thiram, should be sown at a depth of 2-3 cm with seed-cum-fertilizer drill.

Cultivars: Scented rice basmati type and hybrids rice generally perform better for direct-seeded conditions. Rice cultivars suitable for DSR in different areas are listed in Table 1.

Table 1. Rice cultivars suitable for DSR in different areas

Area	Cultivar
Western Uttar Pradesh	Pusa 1121 (Sugandha 4), Pusa 2511 (Sugandha 5), PRH-10,
Haryana	Pusa Basmati-1, KRH-2, Pant Dhan-12, Sharbati, PHB-71
Eastern Uttar Pradesh	NDR 359, Sarjoo 52, Mussorie, Moti, Pusa 44 Nidhi, UPRI-
Tarai of Uttarakhand	92-79, Narendra-359 and PD 4, Sarvati, PR-113, HKR-120,
Bihar	Sarjoo-52 Rajshree, MTU-7029, Satyam, Rajendra Mahsuri-I

Fertilizer management: Apply full dose of P and K (60 kg P₂O₅ and 50 kg K₂O ha⁻¹) just before sowing and 50 kg N at sowing using a seed-cum-fertilizer drill. The subsequent doses of N should be applied using a leaf colour chart (LCC). For guidance of LCC use, refer the section on site-specific nutrient management.

Weed management: Existing and newly-germinated weeds can be knocked down with timely and judicious use of glyphosate or paraquat at 1.0 kg ha⁻¹ using 400 L water ha⁻¹ or mechanically by 1-2 shallow ploughings (zero-harrowing). Glyphosate, a systemic herbicide, is most effective at the active growth stages of weeds, and is preferred to paraquat for controlling perennial weeds, namely *Cynodon dactylon*, *Cyperus rotundus/esculentus*, etc., Its application should be targeted to the actively-growing foliage of weeds, and not to the soil. Whatever spray droplets fall on the ground, is a waste. Similar conditions apply to paraquat, which is a contact herbicide. Paraquat may be used in areas infested mainly with annual weeds at specified rate mentioned above. It controls the perennial weeds too, but their above-ground vegetative parts only. These two herbicides may be applied when there is bright sunshine (which is a pre-requisite for paraquat) and sufficient time, at least 8 hours should elapse between application of herbicide and seeding of rice.

Pre-emergence herbicides such as pendimethalin (1.5 kg ha^{-1}), pretilachlor(S) ($0.5\text{-}0.75 \text{ kg ha}^{-1}$), butachlor (1.5 kg ha^{-1}) may be used in direct-seeded rice for controlling annual grasses, sedges and broad-leaved weeds. Pendimethalin at 1.5 kg ha^{-1} is applied 1-2 days after sowing (DAS) of rice using 500-600 L water ha^{-1} . Pretilachlor(S) is applied within 3 DAS at the rate of $0.5\text{-}0.75 \text{ kg ha}^{-1}$. Sufficient moisture in soil is a pre-requisite for application of these herbicides. Avoid herbicide sprays immediately before or after irrigation or upon rainfall.

Recently, new low-dose chemicals such as bispyribac-Na, azimsulfuron, pyrazosulfuron-ethyl, etc. have become available for post-emergence application in rice.

To knock down mixed populations of weeds (grass and broad-leaved ones), which come up along with rice, apply bispyribac-Na ($20\text{-}25 \text{ g ha}^{-1}$) at 20-25 DAS; pyrazosulfuron-ethyl ($20\text{-}25 \text{ g ha}^{-1}$) at 15-20 DAS; or almix (4 g ha^{-1}) at 20-25 DAS. If there is dominance of only broad-leaved weeds during post-sowing period, 2,4-D ester/sodium salt ($0.5\text{-}0.75 \text{ kg ha}^{-1}$) at 20-25 DAS or pyrazosulfuron-ethyl ($20\text{-}25 \text{ g ha}^{-1}$) at 15-20 DAS may be advocated. Perennial sedges such as *Cyperus rotundus/esculentus*, propagating through under-ground vegetative structures often show tolerance to or escape from these annual weed-killer herbicides (Das, 2001; Kumar *et al.*, 2012). If these perennial sedges or perennial Bermuda grass (*Cynodon dactylon*) dominate in the standing crop of rice, a manual weeding must be given at 30-35 DAS.

Irrigation management: If the moisture in soil is appropriate, seed the rice crop, and irrigate after seeding to facilitate germination. Under the rainfed situations, weeds are allowed to grow for sometimes after pre-monsoon showers and then knocked down using herbicides or by shallow tillage and rice can be seeded subsequently. This practice is known as stale seed bed. With good germination, next irrigation can be given after 7-10 days so that sufficient moisture remains in soil. Subsequent irrigation can be given when fine hair-line cracks appears on the surface. Water stress must be avoided at tillering, panicle initiation and grain filling stages, which are very critical for good yield.

Brown Manuring with *Sesbania*

Traditionally farmers grow green manure crop like *Sesbania* during summer and incorporate it by puddling before transplanting rice seedlings. This means an

additional need for irrigation water for *Sesbania* crop *per se* and fuel costs for incorporating it. Since there is little water in the reservoirs during peak summers, farmers have not been able to take full advantage of green manuring.



Brown manuring

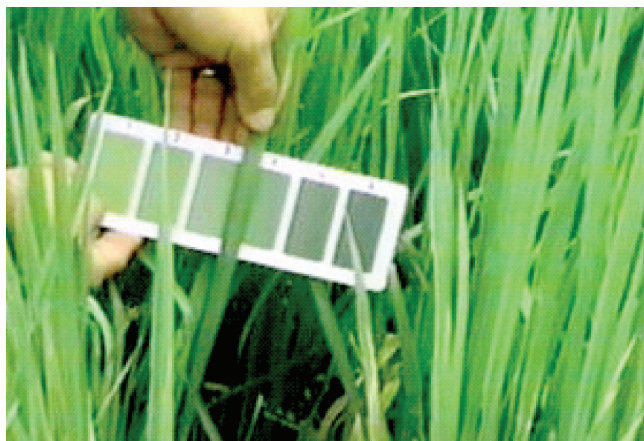
(Photo courtesy: Division of Agronomy, IARI)

In brown manuring, rice and *Sesbania* are sown together and allowed to grow for 25-30 days before knocking down *Sesbania* crop with 2,4-D ester salt at a rate of 0.40-0.50 kg ha⁻¹. The technology smothers weed, reduces herbicide-use, lowers irrigation application, supplies 15-20 kg N ha⁻¹ with a fresh biomass of 10-12 t ha⁻¹, facilitates better emergence of rice where soil crusting occurs, conserves moisture with brown mulch, improves soil C content and increases farmers' income.

Rice and *Sesbania* can be planted with the same drill or *Sesbania* seed can be broadcast before rice sowing. For providing quick surface coverage of the inter-row spaces, use half the total seed of *Sesbania* for broadcast. This practice can also be followed for crops like maize, and the *Sesbania* growing in between the wide inter-row spaces can be killed by 2,4-D or cut manually and spread on surface to act as mulch for moisture and nutrient conservation.

Leaf Colour Chart for Site-Specific Nitrogen Management

Leaf Colour Chart (LCC) is an easy-to-use and inexpensive tool for determining nitrogen status in plants. Use of the LCC promotes timely and efficient use of N



Leaf Colour Chart (LCC) for N application
(Photo courtesy: RWC-IGP, New Delhi)

fertilizer in rice and wheat to save costly fertilizer and minimize the fertilizer-related pollution of surface water and groundwater. It is a promising eco-friendly and inexpensive tool in the hands of the farmers.

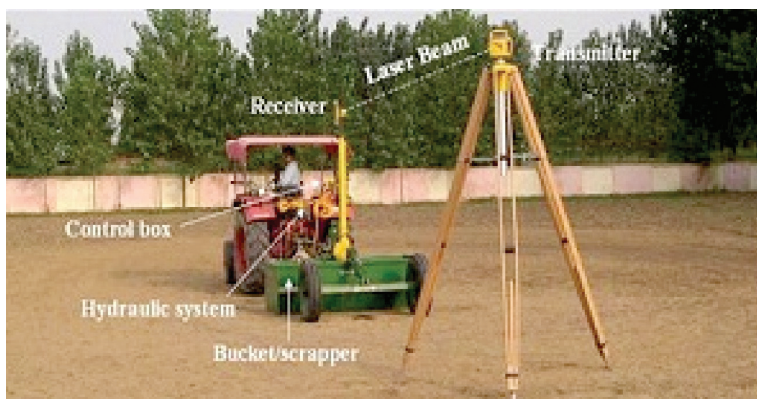
The steps in using a Leaf Colour Chart for achieving best result are listed below:

- At 14 days after transplanting (DAT) or 21 days after direct wet seeding (DAS), randomly select 10 healthy plants in the field where plant distribution is uniform.
- Compare the topmost, fully expanded, and healthy leaf of each of the 10 plants with the LCC. Place the middle part of the leaf on top of the LCC colour strips for comparison. Do not detach the leaf. Take readings at the same time of the day (8-10 AM). Do not expose the LCC to direct sunlight during readings. The same person should take the first up to the last LCC reading.
- If six (6) or more of the 10 leaves show readings below the critical LCC value, apply N as given below:
 - ◆ For wet season non-basmati rice, use LCC critical value 4, and apply 28 kg N ha⁻¹

- ◆ For wet season basmati rice, use LCC critical value 3, and apply 23 kg N ha⁻¹
- ◆ For direct-seeded rice, apply 23 kg N ha⁻¹ as basal, then use LCC critical value 3, and apply 23 kg N ha⁻¹
- ◆ For *boro* rice, apply 23 kg N ha⁻¹ as basal, then use LCC critical value 4 and apply 35 kg N ha⁻¹
- Repeat LCC readings every 7 days for 110-130-day rice crop and every 10 days for more than 130-day crop until first heading. Different sets of 10 leaves can be used for each weekly or 10-day reading.
- If basal fertilizer with N (DAP or NPK compound) is applied 0-14 DAT or 0-14 DAS, the first LCC reading is done at 21-25 DAT or 28-30 DAS instead of 14 DAT or 21 DAS.

Laser Land Levelling

Laser land levelling is the process of smoothening the land surface (± 2 cm) and altering the fields to create a constant slope of 0 to 0.2% using laser equipped drag buckets. This practice makes use of large horsepower tractors and soil movers that are equipped with global positioning systems (GPS) and/or laser-guided instrumentation so that the soil can be moved either by cutting or filling to create the desired slope/level. Laser levelling provides a very accurate, smooth and graded field, which allows ideal control of water distribution with negligible losses,



Laser aided land levelling
(Photo courtesy: RWC-IGP, New Delhi)

thereby improving irrigation efficiency. It facilitates uniformity in the placement of seed/seedlings and fertilizer which helps good plant stand, enhanced nutrient-use efficiency and increased yield. It also reduces the cost of cultivation and increases farmers' income.

Laser land levelling is the most important resource conservation technology, which helps in saving of irrigation water up to 20% and improves the use-efficiency of applied N. There is 3-4% increase in the net area due to fewer requirements of bunds and channels. All these factors lead to about 1% increase in yield. Although the machine is costly (Rs 3.5 lakh, every farmer cannot purchase it; however these are now commonly available on custom hiring basis.

Steps in Laser Land Levelling

Ploughing of field: All surface residues need to be cut or removed before ploughing the field to facilitate the transport of soil. Ploughing of a field should start from the centre outwards when the soil is slightly moist. If the soil is very dry, a one-way disc or mould board plough may be used.

Topographic survey: After the ploughing, a topographic survey should be conducted to record the high and low spots in the field. Adjust the individual positioning of the tripod legs until the base plate is level. Attach the laser transmitter to the base plate. If the laser is not well levelled, adjust the individual screws on the base of the transmitter to get the level indicator (bubble) at the centre. Most lasers will not rotate unless the transmitter is level. When transmitter is level, attach the receiver to the pole and activate the alarm to take field observations. All measurements should be recorded in a field book. The mean height of the field is calculated by taking the sum of all the readings and dividing by the number of readings taken. It is advisable to take readings at regular intervals of 15 × 15 m to achieve a higher precision in land levelling.

Laser levelling of field: Set the average elevation value of the field in the control box. The laser-controlled bucket should be positioned at a point that represents the mean height of the field. The cutting blade should be set slightly above ground level (1.0-2.0 cm). The tractor should then be driven in a circular direction from the high areas to the lower areas in the field. To maximize working efficiency, as soon as the bucket is near filled with soil the operator should turn and drive towards the lower area. Similarly as soon as the bucket is near empty,

the tractor should be turned and driven back to the higher areas. When the whole field has been covered in the circular manner, the tractor and bucket should then do a final levelling pass in long runs from the high end of the field to the lower end. The field should then be re-surveyed to make sure that the desired level of precision has been attained.

Tillage practices to maintain field level after levelling: Initially, a single pass should be made in the centre of the field to move the soil to the right. The tractor is then repositioned at the end of the first run so as to plough the second run outwards from the furrow created. The third plough run then moves the previous ploughed soil back into the depression in the centre of the field. The fourth run then refills the remaining furrow leaving the centre of the field level. The field should then be ploughed on either side of the land until a margin equal to the width of the headland is left. The remainder of the field is then ploughed in a continuous pattern with the final run leaving a drainage furrow beside the bund.

To conclude, the resource conserving technologies have potential to improve the use-efficiency of natural resources such as water, air, fossil fuel and soil. The technologies can improve the sustainability of agriculture by mitigating GHG emissions and adapting to climate changes. A pragmatic roadmap to sustainable agriculture requires integrated emphasis on adoption of resource-conserving technologies, participation of farmers and their collectives, and partnership and support of political and service organizations. Besides these elements, the value-orientation and perception of practitioners towards climate-friendly sustainable agriculture are of paramount importance.

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Prioritizing Climate Change Adaptation Technologies in Agriculture: A Multi-criteria Analysis

H Pathak

Introduction

Climate change represents a complex and strategic risk, and therefore robust adaptation measures that would provide benefits under various future climate scenarios are required (Willows and Connell, 2003). Adaptation assessments are conducted with the aim to identify and evaluate the strength of those measures and serve as inputs for the national adaptation strategies (de Bruin *et al.*, 2009). Adaptation options should be developed by involving local stakeholders and taking care that the gap between top-down and bottom-up approaches to adaptation is bridged. It would provide help to the government in arriving at optimal policy decisions about adaptation measures for allocation of scarce resources. The objectives of the chapter are to outline the approach for identification of potential adaptation options for Indian agriculture, and prioritize the potential adaptation options to respond to the climate change.

Methodology

There are several approaches to arrive at a priority setting for alternative policy options. Metroeconomica (2004) has identified a full range of decision-support tools for option appraisal and regards cost-benefit analysis as a key decision support tool. Janssen and van Herwijnen (2006) have provided a toolbox for multi-criteria decision-making. The evaluation steps of the toolbox include clear problem identification, which covers identification of all the alternatives, selection of a set of criteria and assessment of scores. Then the scores are standardized and the weight of each criterion is determined. The Multi-criteria Analysis (MCA) has been used to assess climate change policy focused on adaptation and mitigation

options (de Bruin *et al.*, 2009). The most suitable approach that the decision-makers can adopt in their decision-making is a multi-level MCA carried out to categorize and rank promising and feasible adaptation options. The MCA is based on the expert judgement, because the definition of the weights to be used in the analysis requires an overview of various issues at stake. The stakeholders representing specific sectors in the society would focus on the sectors of their interest and have an evaluation across different sectors.

In the present methodology, ranking of the adaptation options is done using MCA, a common tool in decision analysis when there are multiple objectives. The MCA uses the judgements of decision-makers or experts or stakeholders as per the importance of each criterion to make rankings of the options according to the weights attached to the various criteria. The method is basically interactive: each individual, group of individuals or decision-makers or group of decision-makers (or experts) can express relevant weights to be used and then the ranking will be updated. The ranking is based on weighted summation of the scores on different criteria (Greening and Bernow, 2004; de Bruin *et al.*, 2009). In criteria weighting, weights are given to each criterion that are supposed to reflect the preferences of the decision-makers and the weighted sum of the different criteria is used to rank the options.

The whole exercise can be undertaken through a workshop in which experts with wide experience on adaptation participate. Experts may be invited from the scientific, technical, and farming communities besides policymakers and youths. The ranking and prioritization of the adaptation options are carried out using the following four steps:

- (1) First, various potential adaptation options based on literature survey are identified and listed for the experts. Additional options are sought from the experts based on their experience and a composite list is prepared.
- (2) Second, the experts are asked to rank (1 to 5 scale) those options based on the qualitative assessment of each priority. Scores are attached for each of the options and for each of the criteria, ranging from 1–5, indicating very low priority (1) to very high priority (5). The number of experts giving a particular rank (1 to 5) to each option is counted which is multiplied by 1, 2, 3, 4 and 5, respectively to get the total score. The 10 most relevant options are short-

listed based on this total score and subjected to further ranking and prioritization.

- (3) Third, ranking of the options is done based on such characteristics as importance, urgency, no-regret, co-benefits for other domains, and mitigation effect as judged by the experts. The importance (i.e., effectiveness in avoiding damages) of an option reflects the level of necessity to implement that option in order to avoid negative impacts. These options can reduce major damages related to climate change and could generate substantial gross benefits. The urgency of the option relates to the need of implementing the adaptation option immediately or whether it is possible to defer action to a later point in time. 'No-regret' options are the adaptation options for which non-climate related benefits, such as improved air quality, will exceed the costs of implementation; hence they will be beneficial irrespective of future climate change taking place. The criterion 'co-benefit' has been specifically designed to reduce the climate change-related vulnerability while producing corollary benefits that are not related to climate change (Abramovitz *et al.*, 2002). In the effect on mitigation, the adaptation options will also induce a reduction of greenhouse gas emissions, and thus score very high on mitigation effect. The ranking is based on a weighted summation of the scores on the criteria (i) importance (weight 40%), (ii) urgency (weight 20%), (iii) no-regret characteristics (weight 15%), (iv) co-benefits (weight 15%) and (v) mitigation effect (weight 10%) (de Bruin *et al.*, 2009).
- (4) Fourth, ranking of the options is done according to the feasibility criteria. The feasibility is scored based on the technical, societal and institutional complexities that accompany the implementation of proposed measures. The following criteria of weightaging is used: technical complexity (20%), societal complexity (40%) and institutional complexity (40%) (de Bruin *et al.*, 2009). Technical complexity refers to the technical difficulties and challenges which accompany the realization of the adaptation option, such as the technical facilities that have to be realized or mobilized; the technological uncertainties which accompany the implementation; the uniqueness of the operation and its risks. Social complexity involves the diversity of values which are at stake when the option will be implemented, the changes which are necessary in the perceptions of stakeholders, the necessity of their cooperation, etc. As the institutional complexity of implementing an adaptation grows, there are more

adjustments of the official, bureaucratic organizations, existing procedures and arrangements necessary, more cooperation between institutional separated domains and thus resulting in a bigger tension with existing practices and structures. Scores are attached on 1–5 scale, ranging from very low (1) to very high (5) complexities.

Potential Adaptation Options in Indian Agriculture: A Case Study

From literature and consultations with the stakeholders, 27 adaptation options were identified. A brief description of these options, which potentially can reduce the vulnerability of the Indian agriculture to the effects of climate change, has been provided in Table 1. As the options have been taken from the literature or have been suggested by a wide range of stakeholders, they include a large variety

Table 1. Climate change adaptation technologies in Indian agriculture based on literature survey and stakeholders consultation

S. No.	Adaptation option	Description of the option
1	Climate-ready crop varieties	Crop varieties tolerant to drought, flood and heat giving higher yield even under extreme climatic conditions
2	Water-saving technologies	Drip, sprinkler and laser-aided land levelling to increase water-use efficiency
3	Changing planting date	Changing planting date (early or late sowing) to avoid heat stress during flowering and maturity of crop
4	Integrated farming system	Inclusion of crop, livestock and fishery in farming system to sustain livelihood, particularly of poor farmers
5	Growing different crops	Growing tolerant/resistant crops to withstand the adverse impacts of climate change
6	Integrated pest management	Combining physical, chemical and biological methods of pest management
7	Crop insurance	Incentives to farmers for covering risks of climatic extremes
8	Organic farming	Use of organic sources of nutrients, avoiding use of chemical pesticides
9	Conservation agriculture	Zero tillage, crop rotation, residue cover of soil

Table 1 contd....

S. No.	Adaptation option	Description of the option
10	Precision farming	Precise management of water, nutrients and pest
11	Improved nutrient management	Site-specific demand-driven and balanced use of nutrients
12	Use of efficient microbes	Use of microbes for enhancing soil fertility and crop productivity
13	Rainwater harvesting	To reduce run-off loss and recharge groundwater
14	Waste land management	Developing wastelands through water and nutrient management for forestry, agro-forestry, grassland and crop production
15	Improved weather-based agro-advisory	Forecasting of weather, particularly extreme events, for crop management planning
16	Growing crops in polyhouse	Protected cultivation of crops in polyhouse for control of temperature, moisture, pests, etc.
17	Increasing irrigation facilities	Bringing more area under irrigation through minor irrigation schemes, check dams, shallow tube-wells
18	Intercropping/mixed cropping	Growing more than one crop to increase productivity and avoid crop failure
19	Creation of seed bank	To provide quality seed to poor farmers, especially useful in case of late onset of monsoon or failure of germination of first sowing
20	Intensifying crop production	Increasing crop production through intensive use of fertilizer and irrigation. This would provide enough food for the years of low production
21	Agro-horticulture, agro-forestry	Agro-horticulture and agro-forestry are more tolerant to drought and flood compared to food crops
22	Cooperative farming	Useful for poor farmers with small landholdings. Farmers joining together can adopt new technologies and bear more risks
23	Use of nano-technology	To increase nutrient- and water-use efficiency
24	Use of non-conventional energy	Use of solar and wind energy to substitute fossil fuel-based conventional energy sources
25	Use of biofuel	Use of biofuel, particularly from non-edible crops and crop residues, in conjunction with fossil fuel
26	Relocating crops into alternate areas	Identifying the crops and regions that are more sensitive to climate changes/variability and relocate them in more suitable areas
27	Indigenous technical knowledge	Harnessing indigenous technical knowledge of farmers for weather forecasting and crop management

Table 2. Prioritization of various adaptation technologies in Indian agriculture based on participants' apparent perception

S. No.	Adaptation option	No. of participants with different ranks*					Total score
		1	2	3	4	5	
1	Climate-ready crop varieties	14	8	6	3	3	129
2	Water-saving technologies	4	7	8	4	3	83
3	Changing planting date	7	3	1	1		52
4	Integrated farming system	2	5	1	8	1	50
5	Growing different crops	1	2	5	3	3	37
6	Integrated pest management	1	1	4	3	1	28
7	Crop insurance	2	1		1	4	20
8	Conservation agriculture	1	1	2		1	16
9	Improved weather-based agro-advisory	1	1	1		3	15
10	Improved nutrient management	1	1	1		3	15
11	Organic farming		1	1	2	1	12
12	Precision farming	1	1			1	10
13	Use of efficient microbes		2			2	10
14	Use of non-conventional energy	1	1			1	10
15	Rainwater harvesting				3	2	8
16	Waste land management			1	2	1	8
17	Cooperative farming		1	1		1	8
18	Increasing irrigation facilities			1	2	1	8
19	Growing crops in polyhouse		1			3	7
20	Intensifying crop production	1			1		7
21	Use of biofuel		1	1			7
22	Relocation of crops into alternate areas	1			1		7
23	Creation of seed bank			1	1	1	6
24	Agro-horticulture, agro-forestry			1	1	1	6
25	Intercropping/mixed cropping			1	1		5
26	Indigenous technical knowledge			1		1	4
27	Use of nano-technology				1		2
	Total No. of participants	38	38	38	38	38	

*1, Extremely relevant; 2, Very highly relevant; 3, Highly relevant; 4, Fairly relevant, 4, Poorly relevant

of technological solutions. Out of these 27 potential options, the 10 adaptation options having the highest priority were identified following the method described in step 2 of the methodology (Table 2). These options were climate-ready crop varieties, water-saving technologies, changing planting dates, integrated farming

system, growing different crops, integrated pest management, crop insurance, conservation agriculture, improved weather-based agro-advisory and improved nutrient management. There were some options which could score low (Table 2). These options were either relatively far-fetched and might not have much impact on adaptation to climate change.

Prioritization of Adaptation Options Based on Participants' Apparent Perception

Table 3 presents the ranked adaptation options according to their importance, urgency, no-regret characteristics, co-benefits for other domains, and mitigation effect. Integrated pest management was ranked at the top, followed by water-saving technologies, conservation agriculture, and crop diversification. Improved nutrient management, improved weather-based agro-advisory and changing planting date were the last three adaptation options. All these 10 options were also ranked for their feasibility in terms of technical, societal and institutional complexities (Table 4).

Table 3. Ranking of various adaptation technologies in Indian agriculture based on importance, urgency of action, no regret character, co-benefit, mitigation potential and economic benefit

Adaptation option	Importance	Urgency of action	No regret	Co-benefit character	Mitigation potential	Rank
Integrated pest management	70	101	131	105	127	96
Water-saving technologies	74	100	96	112	122	93
Conservation agriculture	81	99	120	106	111	97
Crop diversification	62	97	121	98	145	92
Integrated farming system	73	92	134	98	128	95
Crop insurance	62	91	124	116	117	91
Climate-ready variety	52	81	128	115	129	86
Improved nutrient management	70	76	130	105	128	91
Improved weather-based agro-advisory	59	76	128	119	134	89
Changing planting date	73	70	130	101	139	92

Table 4. Ranking of various adaptation technologies in Indian agriculture based on technical, institutional and social complexities

Adaptation option	Technical complexity	Institutional complexity	Social complexity	Rank
Improved weather-based agro-advisory	59	62	57	59
Improved nutrient management	62	54	64	60
Changing planting date	57	65	57	60
Conservation agriculture	60	70	50	60
Climate-ready variety	53	72	55	61
Water-saving technologies	55	64	61	61
Integrated pest management	56	52	72	61
Crop diversification	57	60	63	61
Crop insurance	49	54	77	62
Integrated farming system	51	60	69	62

The strength of the MCA approach is that it provides a ranking of options that can be used in further discussions and decisions on the adaptation strategy. The method is useful in communication with the stakeholders and in raising awareness about the challenges of adaptation and the various options to do so. A set of top priority options could be identified based on expert judgement and at relatively low research costs. A limitation of the approach is that it does not provide a full social cost–benefit analysis of the adaptation technologies.

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Section V

**Vulnerability Assessment for
Climate Change**

Use of Simulation Models for Analysing Vulnerability of Crops to Climate Change

S Naresh Kumar

Introduction

Climate change has been defined by UNFCCC as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods”. Increased anthropogenic activities are leading to rise in the concentration of greenhouse gases, causing the global climate change. According to IPCC (2007), this has resulted in warming of the climate system by 0.74 °C between 1906 and 2005. The projected increase in temperature for south Asia is in the range of 0.5-1.2 °C by 2020, 0.88-3.16 °C by 2050 and 1.56-5.44 °C by 2080, depending on the scenario of future development. The projections also indicate increase in the frequency of droughts, floods, and extreme events of temperature and rainfall. These environmental changes are likely to have increased pressure on Indian agriculture, in addition to the on-going stresses of yield stagnation, land-use, competition for land, water and other resources, and globalization. Increasing climatic variability associated with global warming will result in considerable seasonal/annual fluctuations in food production. Thus, it is important to understand, quantify and derive potential adaptation options and strategies for not only minimizing the negative impacts of climate change but also to harness the positive impacts, if any.

Quantification of Impacts of Climate Change

The quantification of impacts of major climate change parameters such as change in temperature and rainfall and higher CO₂ levels on crops are being studied using two approaches, viz. field or controlled environment experiments and simulation models. In the field experimentations, quantifications are done by

growing crops in the Open-Top Chamber (OTC) or in Free Atmospheric Carbon dioxide Enrichment (FACE), Free Atmospheric Temperature Elevation (FATE) facilities and in rain-out shelters. These studies provide vital information on crop response to the elevated CO₂ level or increased temperature or to both and to change in rainfall, in spite of being costly and time-taking procedure. But, the information generated cannot be generalized for regional/ state or national level. The other approach is to use well validated simulation models. Simulation models are strong tools which provide opportunity to use various climate change scenarios in combination with different management parameters for analyzing the regional impacts (Naresh Kumar and Aggarwal, 2009). Apart from these, well-developed crop simulation models provide opportunity to assess the impacts of climatic variability on crop growth. Further, crop simulation models coupled with GIS become strong tools for not only impact, adaptation and vulnerability assessments, but also for studying land-use change and land-use plan.

Climate Change Impact Assessments using Simulation Models

Crop growth simulation models are used to quantify the impacts of elevated temperature, increased CO₂ level, change in rainfall, etc. individually or in combination. These analyses do provide vital information with reference to 'fixed changes in weather factors'. Another approach is to use the climate scenarios for impact assessments, wherein the global or regional climate model outputs of climate data are used as input for the crop simulation models to quantify the impacts. In fact, the research on climate change uses a cascade of simulation models (Naresh Kumar *et al.*, 2011). The output from a higher level model is input into the next lower level model. For instance, the General Circulation Models (GCM) or Regional Climate Models (RCM) outputs on climate scenarios are used as input into the impact models such as crop models for impact analysis. The impact analysis models such as crop simulation models, hydrological models, etc, can be used independently or inter-dependently for impact assessments. The agricultural economic models, in general, depend on the crop simulation models for estimating the crop yields in the changed climates for further economic impact assessment. It needs to be realized that all these models, which are the simplified representations of complex natural, biophysical and socio-economic interactions, have limitations, assumptions and work within certain boundary conditions. In

spite of unavoidable uncertainties in modelling, particularly with respect to climate models, the impact assessments at regional and national levels provide direction on possible impacts and also provide insights for better preparedness to reduce the adverse impacts of climate change.

Before we go into more details about scenarios, let us understand some terms as defined by IPCC.

Projection: The term “projection” is used in two senses in the climate change literature. In the general usage, a projection can be regarded as any description of the future and the pathway leading to it. However, a more specific interpretation has been attached to the term “climate projection” by the IPCC when referring to the model-derived estimates of future climate.

Baseline/Reference: The baseline (or reference) is any datum against which change is measured. It might be a “current baseline”, in which case it represents observable, present-day conditions. It can be a “future baseline”, which is a projected future set of conditions, excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.

Forecast/Prediction: When a projection is branded “most likely” it becomes a forecast or prediction. A forecast is often obtained using deterministic models, possibly a set of these, outputs of which can enable some level of confidence to be attached to projections.

Scenario: A scenario is a coherent, internally consistent and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold. A projection may serve as the raw material for a scenario, but scenarios often require additional information (e.g., about baseline conditions). A set of scenarios is often adopted to reflect, as well as possible, the range of uncertainty in projections. Other terms that have been used as synonyms for scenario are “characterization”, “storyline” and “construction”.

Having known these terms, let us now understand different scenarios which are depicted in Figure 1.

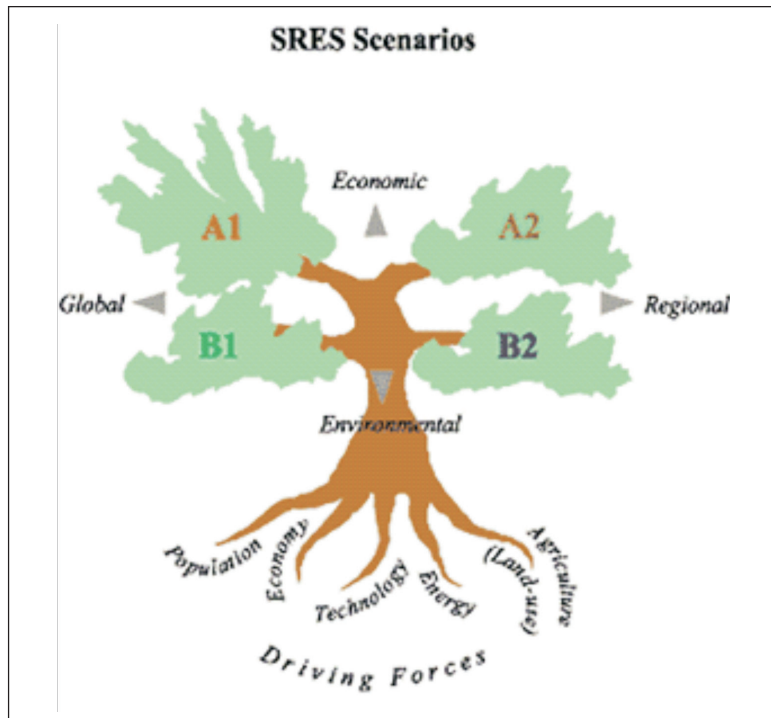


Figure 1. Various SRES scenarios (developmental pathways)
(Source: IPCC AR 3, 2001)

The climate change analysis is carried out in several steps. Initially, socio-economic models are used for deriving the GHG emissions in future developmental scenarios. Depending on the future plausible developmental paths adopted by the world, the emission scenarios are broadly categorized into A1, A2, B1 and B2 scenarios (IPCC, 2001). Of these, A1 and B1 indicate more global-level socio-economic changes, while A2 and B2 indicate more regional-based socio-economic changes. The A1 and A2 scenarios are more economic oriented without much concern for environmental sustainability, whereas the B1 and B2 developmental pathways address the environmental issues while implementing the economic policies.

Depending on the plausible developmental pathways, the GHG emission scenarios also change. For instance, in a developmental pathway which

intensively uses the fossil fuels (A1F scenario), the CO₂ concentrations are projected to be in the range of 386 to 495 ppm by 2020 (which means a 30-year period from 2010 to 2039), 555 to 702 ppm by 2050 (i.e., 2040-2069) and 786 to 958 ppm by 2080 (i.e., 2070-2099) as against 386 to 457 ppm by 2020, 482 to 518 ppm by 2050 and 530 to 540 ppm by 2080 in a developmental pathway (B1) which uses eco-friendly technologies. Similarly, the concentrations of other GHGs will also change. The differences in GHG emissions, derived from the socio-economic models, depending on plausible developmental pathways (A1, A2, B1, B2), in turn, result in variations in the concentration of GHGs in the atmosphere. The concentration of GHGs and several baseline factors are the inputs for the global climate models, which provide climate data for the future periods. These are called climate scenarios, which in general are for 2020 (2010-2039), 2050 (2040-2069), and 2080 (2070-2099) periods. The magnitude of projected change in temperatures, rainfall, etc. depends on the developmental pathways which the world is likely to adapt. For instance, in the B (B1 and B2) scenarios, the magnitude of rise in temperature is projected to be less as compared to that in the A (A1 and A2) scenarios.

What are GCMs and RCMs?

General Circulation Models (GCMs) representing physical processes in the atmosphere, ocean, cryosphere and land surface are the most advanced tools currently available for simulating the response of the global climate system to increasing concentration of greenhouse gases. The GCMs depict the climate using a three-dimensional grid over the globe, typically having a horizontal resolution between 250 km and 600 km (approx. $2.5^\circ \times 2.5^\circ$). Their resolution is thus quite coarse relative to the scale of exposure units in most impact assessments, but these GCMs are quite useful for global assessments. These models project climate change scenarios for various regions of the world keeping in view (i) socio-economic aspects, (ii) technological and population growth (iii) green house gas emissions due to these two aspect, and (iv) Land surface and vegetation details. Thus, use of scenario outputs of GCM becomes imperative in the climate change research. There are about 24 GCMs which are being used for developing the climate scenarios. Such models include HadCM3 (UK MetOffice, UK), ECHAM5-OM (Max-Planck-Institute for Meteorology, Germany), CGCM3 (Canadian Center for Climate Modeling and Analysis, Canada), etc.

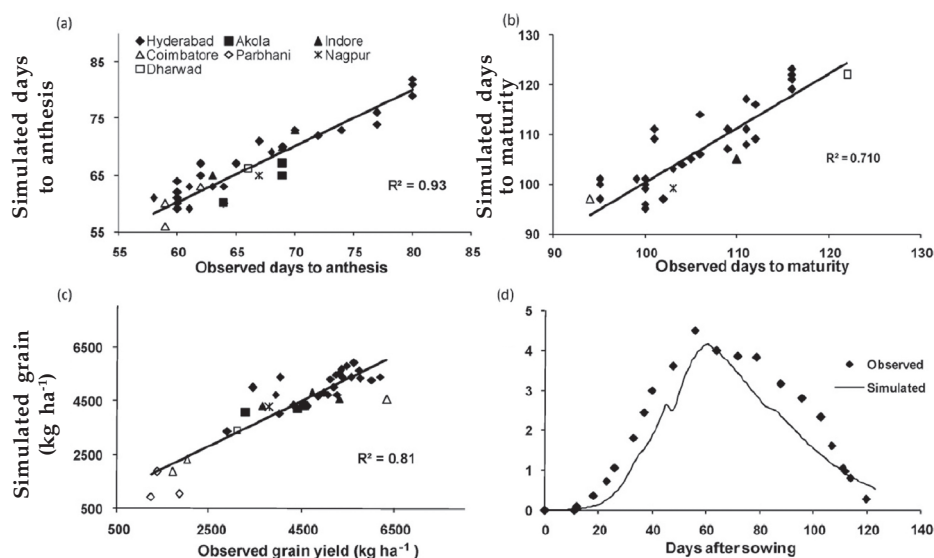
Since the GCMs are of coarse resolution, the regional climate models (RCMs) are run with the inputs from GCMs as well as from local topographical information. These models are of finer resolution, i.e., about 25 km × 25 km or less and thus are vital for regional impact assessments. While simpler models have also been used to provide globally- or regionally-averaged estimates of the climate response, only GCMs, possibly in conjunction with nested regional models, have the potential to provide geographically and physically consistent estimates of regional climate change which are required in impact analysis. For instance, crop simulations models are used for assessing the impacts of climate change on crops. Similarly, hydrological models are used for assessing the impacts on water resources.

Steps in Crop Simulation Analysis

Before simulation analysis, as a first step one needs to be clear about the information or assessment sought, availability and suitability of data, models, modelling skills, etc. These have been outlined in the following.

1. Minimal database of experimental records on the following parameters:
 - a. Varietal characteristics such as days to flowing, maturity, time series data on LAI, dry matter and crop nitrogen uptake, and grain yield, grain nitrogen and number of grains/m².
 - b. Crop management information such as time and depth of sowing, time and dose of application of fertilizers, organic matter and irrigation, pest incidence, etc.
 - c. Soil characteristics such as texture, water holding characteristics, bulk density and soil pH in different depths of soil layers.
2. Daily weather data (minimum and maximum temperatures, rain fall, wind velocity, vapour pressure and solar radiation).
3. Calibration and validation of simulation models: Although the simulation models are flexible enough to perform under a variety of environments and farming conditions, calibration of model is necessary before running the model for the study area. For this, results from the detailed experiments on varietal performance, fertilizer trials, multi-location trails can be made use of. The calibrated model can be used to simulate the crop growth performance in other set of experiments consisting of various treatments for validating the

model performance under a range of conditions. This validated model can be used for simulating impacts in the selected region. A typical calibration and validation approach has been depicted in Figure 2.



(Source: Srivastava *et al.*, 2010)

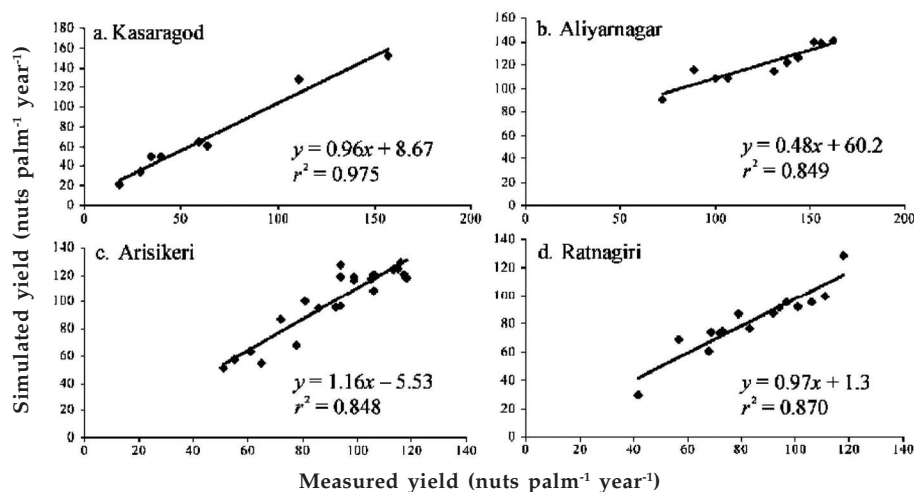


Figure 2. A typical calibration and validation approach
(Source: Naresh Kumar *et al.*, 2008)

- a. Calibration of a model to simulate the performance of crop in an experiment, which has time series data on crop performance such as phenology, LAI, dry matter accumulation and yield.
- b. Validation of the calibrated model against the data from other experiments/locations/conditions where minimum information on crop management, and crop performance in terms of phenology (days to 50% flowering and physiological maturity), grain yield and dry matter at harvest are available.
6. Model performance in simulating the observed performance of crop under variable conditions should be assessed through various statistical parameters, viz. model bias error (MBE), root mean square error (RMSE), index of agreement (IA), model efficiency (ME), etc.
7. The calibrated and validated model is now ready for application for various studies.

Application of Crop Models for Climate Change Impact Assessments

1. **Baseline Weather Data:** For climate change impact assessments, one needs to take the baseline data (1960-1990 or any other set of past 30 years defined period). This data can be of observed one or that from model outputs.
2. **Climate Scenarios:** Data on climate scenarios (from either GCMs or RCMs) need to be converted to suitable input format specific to a model. Before that, the approaches followed for using the climate data should be clear. Although several approaches are being tested, two methods are described here.
 - a. In the first approach, climate scenario data as such may be used for making the input weather files. In this case, the baseline and scenario data are model derived.
 - b. In the second approach, the outputs from climate models need to be processed to derive the difference fields from baseline values for the respective scenario, which is referred to as the delta method. These difference fields should be coupled to the baseline weather data to get the scenario climate data. The major advantage of this method is the overcoming of biases of the climate model for baseline weather. Apart from this, frequency of occurrence of climatic extreme events such as higher/low rainfall events and high temperature events is inherently accounted for. However, the assumption of distribution of rainfall

remaining similar in future scenarios as that of baseline period is a major limitation of this method.

- c. The projected carbon dioxide levels as per Bern CC model for scenario also need to be included in the model for simulations. In case outputs on CO₂ concentrations from other models are used by GCM, respective values should be used.
- d. Care need to be taken to simulate the individual years and then take the mean of 30 years as the mean scenario year. It is advised not to designate the individual year (2021, 2022, 2023, etc.) to future scenario data as they are scenario projections and not forecasts.
- e. It is also desirable to use ensemble of models and scenarios for impact assessments for minimizing the uncertainty in assessments.
- f. The model integration, wherein several models for different sectors are used for developing integrated assessments, is the need of the hour.

For instance, if InfoCrop model is used for simulating climate change impacts, the data need to be processed to input into the model. InfoCrop is a generic crop growth model that can simulate the effects of weather, soil, agronomic managements (including planting, nitrogen, residue and irrigation) and major pests on crop growth and yield. The model considers different crop development and growth processes influencing the simulation of yield. The total crop growth period in the model is divided into three phases, viz., sowing to seedling emergence, seedling emergence to anthesis and storage organ filling phases. The model requires various varietal coefficients, viz. thermal time for phenological stages, potential grain weight, specific leaf area, maximum relative growth rate, maximum radiation use efficiency, etc. Crop management inputs into the model include time of sowing, application schedule and amount of fertilizer and irrigation. Soil input data include soil pH, soil texture, thickness, bulk density, saturated hydraulic conductivity, soil organic carbon, slope, soil water holding capacity and permanent wilting point. Location-wise daily weather data (solar radiation, maximum and minimum temperatures, rainfall, wind speed, vapour pressure) are also required to simulate crop performance. For more details on InfoCrop, refer to the manual prepared by Aggarwal *et al.* (2004) and for details on how it simulates the effects of temperature, CO₂ and rainfall, it is suggested to refer to Naresh Kumar *et al.* (2011).

Estimating Baseline Yields: The mean of 30 years yield should be taken as the baseline yield.

Simulating Yields in Future Scenarios: To express the impacts on yields, the net change in yield in climate change scenario should be calculated and expressed as the percentage change from baseline mean yield. These are called the impacts which can be calibrated to a specific base-yield and per cent deviations from such yields in a given scenario.

Simulating Yield Gains due to Adaptation Options: The adaptation analysis can be done by quantifying the response of different varieties, sowing time, nutrient management, water management, introduction of new crops, shift in cropping sequences, altered resource management and introduction of new technologies, etc., in various climate change scenarios so as to derive the best suitable technology package for reducing impacts of climate change at the regional level and then up-scaling to state and national level. The difference between mean yields in future scenario (impact) and mean yields due to adaptation options in future scenario is called the adaptation gain and may be expressed as per cent gain over impacts. These are called adaptation gains. If the crop yields are still negative even after adaptation, the magnitude represents vulnerability of crop.

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Vulnerability of the Indo-Gangetic Plains to Climate Change

Anita Chaudhary, VK Sehgal, Manoranjan Das and H Pathak

Introduction

In India, the impacts of climate change and variability have been an important concern for sustainable agriculture because of food security and environment preservation. Agriculture will be adversely affected by an overall increase or decrease in rainfall and also by the increase or decrease in temperature at different growth stages of crops. There are two approaches to map the vulnerability. One approach considers vulnerability as the 'End point', which is the net impact of climate change as it considers the residual impacts of climate change by taking into account the adaptation options as well. This approach starts with the future emission projection trends, followed by development of climate change scenarios and studying the impact and identification of adaptive options (O'Brien *et al.*, 2004). The other approach considers vulnerability as the 'Starting point' and has its origin in assessing the vulnerability of social sector to food insecurity and natural hazards (Bohle *et al.*, 1994; Cutter, 1996). This approach takes into account the existing state which determines the capacity to cope with the hazard, instead of future conditions, thereby determining the present-day vulnerability.

Methodology for Computing Vulnerability Index of a Region to Climate Change

The indicator approach is the most common method adopted for quantifying vulnerability in the global change scenario. The indicator approach can be applied at different scales, viz. farm level, state/district level, and national level and is valuable for practical decision-making processes, by the policy makers for equitable and sustainable development. This approach uses a specific set or combination of indicators (proxy indicators) for measuring the vulnerability by either

computing indices, or taking averages or weighted averages for those selected indicators. Vulnerability is a function of three components: exposure, sensitivity and adaptive capacity (resilience) which are influenced by a range of biophysical and socio-economic factors (IPCC, 2007). Exposure can be termed as the stress such as magnitude of changes to a region's climate variables (e.g., temperature, precipitation, extreme weather events). The sensitivity describes the human–environmental conditions that can worsen the extreme event and ameliorate the event and the adaptive capacity indicates the potential to implement adaptation measures that can mitigate the potential impacts.

Computation of Vulnerability Index through ESA Approach

Steps for computing vulnerability index for the farming sector at the regional scale to climate change has been illustrated with the Indo-Gangetic Plains (IGP) as a case study.

Step 1: Collection of Data for Determinants of Vulnerability

District-wise data of a region have to be collected for different determinants of vulnerability in terms of exposure, sensitivity and adaptive capacity of that particular region. These parameters may vary from region to region.

Step 2: Standardization of Data

As vulnerability depends largely on exposure and sensitivity, and the coping capacity, therefore it may be formulated as:

$$V = f(I - AC)$$

where, V is vulnerability, I is potential impact (exposure + sensitivity), and AC is adaptive capacity. A higher adaptive capacity is associated with a lower vulnerability, while a higher impact is associated with a higher vulnerability. To ensure that all the indicators are comparable, some form of standardization is carried out (Vincent, 2004). All the variables in the vulnerability indices are normalized to a range of 0 to 100 by the following general formula:

$$\text{Index value} = \frac{(\text{Actual value} - \text{minimum value})}{(\text{Maximum value} - \text{minimum value})} \times 100 \quad \dots(2)$$

The high index values mean high vulnerability in all the cases but for indicators such as average landholding size, human development index and average yield, etc. hypothesized to decrease vulnerability; the index values are reversed by subtracting it from 100 i.e. [100 – index value].

Step 3: Assignment of Weight through PCA Approach

After standardizing the data, weights were attached to the indicators by using principal component analysis (PCA) with the help of statistical software like SAS. The first principal component explains most of the variation, so the eigen vector for first principal component (PCA 1) was taken as the scoring factor or weight for the indicators.

Step 4: Computation of Vulnerability Index

The assigned weights are then used to compute an overall vulnerability index by applying formula (3) (Filmer and Pritchett, 2001):

$$v_j = \sum_{i=1}^k [b_i (a_{ij} - x_i)] / s_i \quad \dots(3)$$

where, v_j is the vulnerability index for the j^{th} district, b_i is the weight from PCA 1 for the i^{th} indicator, a_{ij} is the i^{th} indicator value of the j^{th} district, x_i is the i^{th} mean indicator value, and s_i is the standard deviation of the i^{th} indicator.

Step 5: Interpretation of the Data

Only first six principal components were significant (based on the Kaiser criterion of an eigen value greater than 1). These six components could explain more than 77 per cent of the total variation in the data set (Table 1). Then scoring factor or weight was assigned to all indicators, by taking the weights those assigned to the indicators in the first principal component (Table 2). The districts which showed high vulnerability index are more vulnerable to climate change variations. Ranking of all the 161 districts of the Indo-Gangetic-Plains (IGP) was done according to their vulnerability index (V.I.) value. According to their vulnerability index, all the districts were classified into 4 classes, viz. Extremely vulnerable, Highly vulnerable, Moderately vulnerable, and Low vulnerable. Then, vulnerability map (Figure 2) of the whole IGP was drawn with respect to their vulnerability index with Arc GIS software ver.10. The map depicted very clearly that most of the

Table 1: Principal components with their eigen values and proportion of variation (IGP)

Principal components	Eigen value	Proportion	Cumulative value
1	8.57	0.408	0.41
2	2.39	0.114	0.52
3	1.73	0.082	0.60
4	1.38	0.066	0.67
5	1.18	0.056	0.73
6	1.00	0.048	0.77
7	0.80	0.038	0.81
8	0.68	0.032	0.84
9	0.61	0.029	0.87
10	0.53	0.025	0.90
11	0.39	0.019	0.92
12	0.38	0.018	0.93
13	0.33	0.016	0.95
14	0.29	0.014	0.96
15	0.27	0.013	0.98
16	0.16	0.008	0.98
17	0.12	0.006	0.98
18	0.08	0.004	0.99
19	0.08	0.004	0.99
20	0.05	0.002	0.99
21	0.02	0.001	1.00

Table 2: Scoring factor and standard deviation of different indicators

Indicators	Mean value	Standard deviation	Scoring factor
T_{Max} <i>Kharif</i>	61.03	19.78	0.28
T_{Min} <i>Kharif</i>	68.17	23.27	0.27
T_{Max} <i>Rabi</i>	58.72	20.69	0.31
T_{Min} <i>Rabi</i>	62.08	25.22	0.32
Drought severity (<i>Kharif</i>)	48.79	18.19	0.03
Drought severity (<i>Rabi</i>)	20.63	14.98	0.08
Flood severity (<i>Kharif</i>)	38.11	21.09	-0.09
Flood severity (<i>Rabi</i>)	31.37	14.65	-0.15
Organic carbon (kg/sq m)	65.16	15.59	-0.19
Available water capacity (mm / 1 m soil depth)	48.63	18.21	-0.02
Population density (Census 2001)	20.77	13.79	0.08
Average yield (kg ha ⁻¹)	61.23	23.54	0.32
Net sown area/ total geographical area	60.30	18.80	-0.19
Avg. landholding size (ha/farmer)	85.26	17.69	0.28
Human development index	50.52	20.81	0.23
Percentage of villages with electricity (power supply)	35.71	30.05	0.28
Percentage of villages with road connectivity	46.52	29.77	0.30
Cropping intensity (%)	67.75	15.82	0.15
NPK fertilizer consumption (kg ha ⁻¹)	65.12	18.98	0.21
Percentage area irrigated	49.16	25.74	0.24
Livestock density 2003	72.03	18.81	-0.12

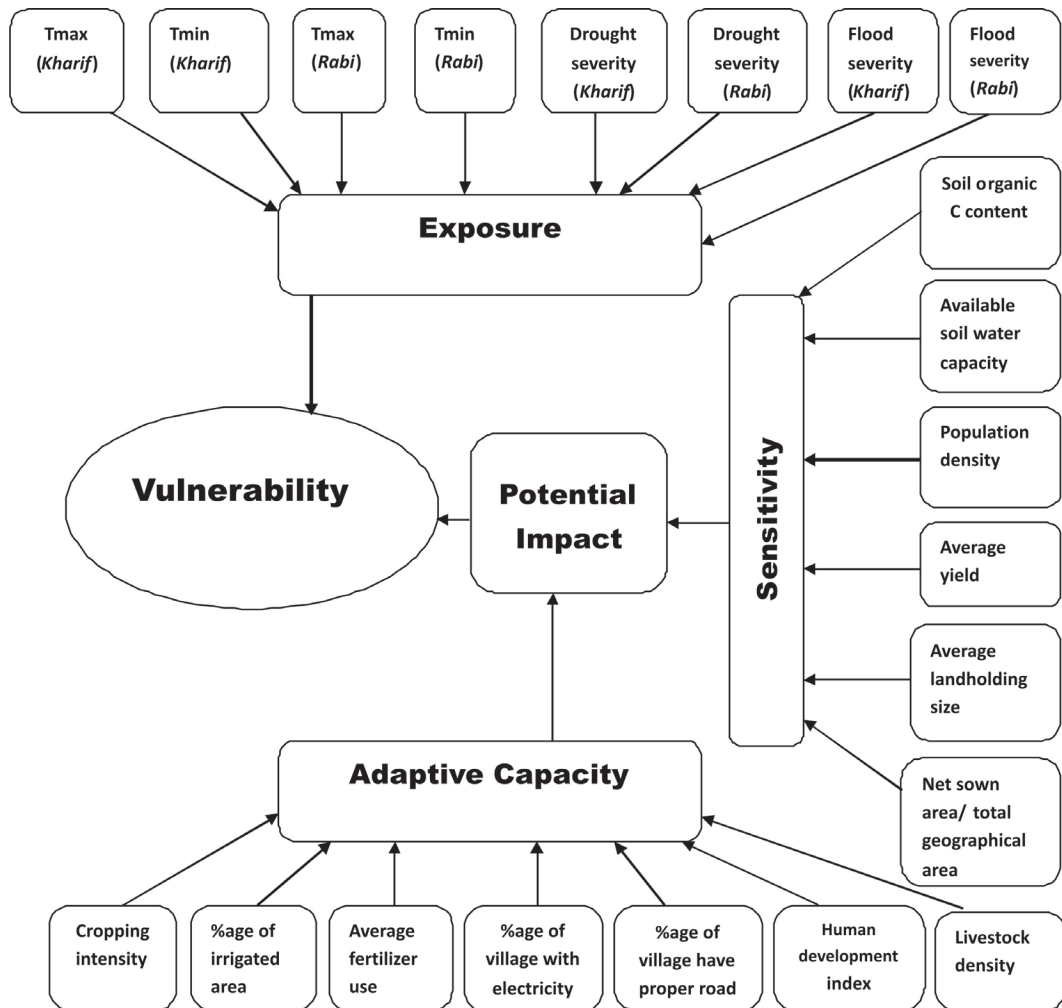


Figure 1. Determinants of exposure, sensitivity and adaptive capacity for computation of vulnerability index of overall vulnerability (Tmax, Maximum temperature; Tmin, Minimum temperature)

districts of Bihar are extremely vulnerable as compared to districts of Punjab, where most of the districts are less vulnerable. Kishanganj of Bihar was found to be most vulnerable with V.I value of 4.687 and Fatehgarh Sahib of Punjab was the least vulnerable district with V.I value of -7.346 among all IGP districts.

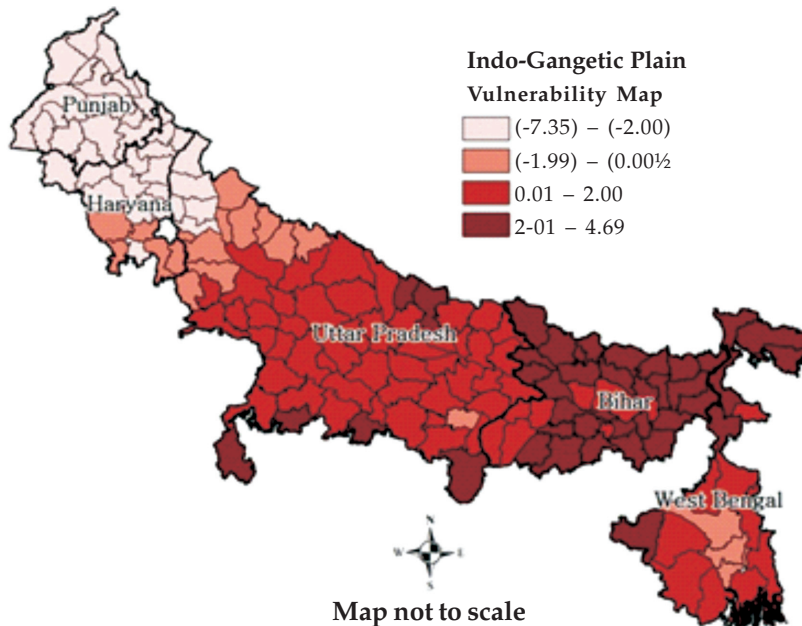


Figure 2. Vulnerability map of Indo-Gangetic Plain (IGP) region to climate change

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Section VI

Mitigation of Greenhouse Gas Emission

Carbon Sequestration Potential of Soil

B Chakrabarti, N Jain, RC Harit and H Pathak

Introduction

Soil can act as a major sink of carbon and can play an important role in reducing level of greenhouse gases (GHGs) in the atmosphere through carbon (C) sequestration. Mitigation of CO₂ emission from agriculture can be achieved by increasing C sequestration in soil, which implies storage of C as soil organic matter (Lal, 2004). Soil management practices such as tillage, fertilizer, irrigation, crop residue management, etc. modify soil C stocks to varying degrees. Reducing the intensity and frequency of ploughing and leaving crop residues on the soil surface as mulch are important strategies for enhancing soil organic carbon (SOC) content. Judicious nutrient management is crucial to SOC sequestration in tropical soils (Battacharya *et al.*, 2007; Mandal *et al.*, 2007). Long-term manure application increases the SOC pool (Gilley and Risse, 2000), and the effects may persist for a century (Compton and Boone, 2000). Although both organic and inorganic forms of C are found in soils, land use and management typically have a larger impact on organic C. There are several national and regional estimates of C sequestration potential in cropland soils (Gupta and Rao, 1994; Lal and Bruce, 1999). With a large land area and diverse ecoregions, there is a considerable potential of terrestrial/soil carbon sequestration in India (Lal, 2004).

In order to estimate the changes in soil carbon stock in cultivated land, one needs to have an estimate of the cropland area and the time period. According to IPCC (2007), soil carbon inventories can be developed using a Tier 1, 2, or 3 approaches with each successive Tier requiring more details and resources than the previous one. Change in soil organic C (SOC) stocks in soils can be calculated by subtracting C stock at the end year of an inventory time period (SOC₀) from the C stock at the beginning of the inventory time period [SOC_(0-T)] and dividing by the time period for transition between equilibrium SOC values.

Tier 1 Approach

In Tier 1 approach changes in soil C stocks are calculated based on C stock after the management change relative to the carbon stock in a reference condition, i.e. by Equation (1):

$$\Delta C = (SOC_0 - SOC_{0-T})/T \quad \dots(1)$$

where, ΔC is the annual change in C stock in mineral soils ($Mg\ C\ yr^{-1}$), SOC_0 is the SOC stock in the last year of an inventory time period ($Mg\ C$), $SOC_{(0-T)}$ is the SOC stock at the beginning of the inventory time period ($Mg\ C$), and T is the number of years over a single inventory time period (yr).

The SOC_0 and SOC_{0-T} are calculated using Equation (2), where the reference carbon stocks (SOC_{REF}) and stock change factors are assigned according to the land-use and management activities and corresponding areas at each of the points in time (time = 0 and time = 0-T).

$$SOC = SOC_{REF} * F_{LU} * F_{MG} * F_I * A \quad \dots(2)$$

where, F_{LU} is the stock change factor for land-use systems or sub-system for a particular land-use, F_{MG} is the stock change factor for management regime, F_I is the stock change factor for input of organic matter, and A is the land area of the stratum being estimated (ha).

All lands in the stratum should have common biophysical conditions (i.e., climate and soil type) and management history over the inventory time period to be treated together for analytical purposes. The stock change factors are broadly defined and include: (i) a land-use factor (F_{LU}) that reflects C stock changes associated with type of land-use, (ii) a management factor (F_{MG}) representing the principal management practice specific to the land-use sector (e.g., different tillage practices in croplands), and (iii) an input factor (F_I) representing different levels of C input to soil (IPCC, 2007).

Default reference SOC stocks (SOC_{REF}) for soils ($Mg\ C\ ha^{-1}$ in 0-30 cm depth) of various regions and climate are given by IPCC (Table 1). However, these can be calculated for a given location using Equation (3):

$$SOC_{REF} = SOC * BD * T \quad \dots(3)$$

Table 1. Default reference soil organic carbon stocks (SOC_{REF}) for soils in 0-30 cm depth (Mg C ha^{-1})

Climate	High activity clay soils ^a	Low activity clay soils ^b	Sandy soils ^c
Tropical dry	38	35	31
Tropical moist	65	47	39
Tropical wet	44	60	66
Tropical montane	88	63	34

Source: Modified from IPCC (2007)

Notes: ^aHigh activity clay soils are dominated by 2:1 silicate clay minerals and include soil orders like Mollisol, Vertisol, high base status Alfisol, Aridisol and Inceptisol.

^bLow activity clay soils are dominated by 1:1 clay minerals and amorphous iron and aluminium oxides and include soil orders like Ultisol, Oxisol and acidic Alfisol.

^cThese includes all soils having >70% sand and <8% clay, based on standard textural analysis.

where, SOC_{REF} is the mass of SOC (Mg ha^{-1}) at the reference site, SOC is the organic C content in soil (%), BD is the bulk density (Mg m^{-3}), and T is the thickness of surface layer (cm).

Steps for Estimating Soil C Stock Change for Cultivated Soils

Following steps are involved for estimating soil C stock change for cultivate soils:

1. Collection and organization of data for soil type, climate, cropping system and management practices of the region for the study period.
2. Determination of area under cultivation at the beginning of the study period.
3. Dividing the study region into climatic divisions that can be represented by individual climate time series of monthly precipitation, and maximum & minimum temperatures.
4. Identifying the distribution of soil textures on the agricultural land for each climatic division.
5. Identifying primary crop rotations followed and assigning a land-use factor (F_{LU}), management factor (F_{MG}) and C input levels (F_{I}) to each cropland. In case of non-availability of measured values, the default values given by the IPCC (2007) can be used (Table 2).

6. Establishing initial reference C stock values (SOC_{REF}) from Table 1 based on climate and soil type.
7. Multiplying the factors (F_{LU} , F_{MG} , F_I) by the reference soil C stock (SOC_{REF}) to estimate an 'initial' soil organic C stock (SOC_{0-T}) for the inventory time period.
8. Estimating the final soil organic C stock (SOC_0) by repeating Steps 1 to 7 using same reference C stock (SOC_{REF}), but with factors (F_{LU} , F_{MG} , F_I) that represent conditions in the last inventory year.
9. Calculating average annual change in soil organic C (ΔC) by subtracting the 'initial' soil organic C stock (SOC_{0-T}) from the final soil organic C stock (SOC_0), and then dividing by the number of years.

Table 2. Relative stock change factors (F_{LU} , F_{MG} , and F_I) for different management activities over 20 years on cropland in tropical temperature regime

Stock change factor	Level	Moisture regime	Default factor	Error (%)
Land use (F_{LU})	Long-term cultivated	Dry	0.58	± 61
		Moist/Wet	0.48	± 46
Land use (F_{LU})	Paddy rice	Dry and Moist/Wet	1.10	± 50
Land use (F_{LU})	Set aside < 20 years	Dry	0.93	± 11
		Moist/Wet	0.82	± 17
Tillage (F_{MG})	Full	Dry and Moist/Wet	1.00	NA
Tillage (F_{MG})	Reduced	Dry	1.09	± 9
		Moist/Wet	1.15	± 8
Tillage (F_{MG})	No-till	Dry	1.17	± 8
		Moist/Wet	1.22	± 7
Input (F_I)	Low	Dry	0.95	± 13
		Moist/Wet	0.92	± 14
Input (F_I)	Medium	Dry & Moist/Wet	1.00	NA
Input (F_I)	High without manure	Dry	1.04	± 13
		Moist/Wet	1.11	± 10
Input (F_I)	High with manure	Dry	1.37	± 12
		Moist/Wet	1.44	± 13

Source: Modified from IPCC (2007)

Tier 2 Approach

The Tier 2 approach involves a more detailed stratification of management systems than in Tier 1. This includes further subdivisions of cropping pattern and input management (i.e., low, medium, high, and high with amendment), rice cultivation, perennial cropping systems, etc. and also involves finer division of climate regions and soil types depending on the availability of data (IPCC, 2007).

Tier 3 Approach

The Tier 3 approach is used to estimate SOC stock with the help of dynamic simulation models or direct measurement based inventory preparation. It needs large amount of detailed data on the combinations of climate, soil, topographic and management, relative to the Tiers 1 and 2 methods. But the exact requirements will depend on the input data requirement of the model or measurement design.

Carbon sequestration potential of soil can also be determined following the methodology described by Pathak *et al.* (2011). In this method, C sequestration is calculated only in terms of increase in C stock in soil. Data on initial and final SOC concentrations in soil are collected for different fertilizer and manure treatments. The mass of SOC in the surface layer (0–15 cm) of soil is calculated as per Equation (4):

$$\text{MSOC} = \text{SOC} \times \text{BD} \times T \quad \dots(4)$$

where, MSOC is the mass of SOC (Mg ha^{-1}), SOC is the organic C concentration in soil (%), BD is the bulk density (Mg m^{-3}), and T is the thickness of surface layer (cm).

Carbon sequestration potential (CSP) is calculated by expression (5):

$$\text{CSP_NPK} = (\text{MSOC_NPK}) - (\text{MSOC_Control}) \quad \dots(5)$$

where, CSP_NPK is the CSP with balanced NPK use (Mg ha^{-1}), MSOC_NPK is the final SOC in the NPK treatment (Mg ha^{-1}), and MSOC_Control is the final SOC in the control treatment (Mg ha^{-1}). Similarly, CSP can be calculated for any treatment like FYM application, integrated nutrient management, etc.

Rate of C sequestration (CSP Rate) in $\text{Mg ha}^{-1} \text{ yr}^{-1}$ is calculated as per Equation (6):

$$\text{CSP Rate} = \text{CSP}_S / D \quad \dots(6)$$

where, CSP_S is the CSP in a particular treatment (Mg ha^{-1}) and D is the duration of the experiment (number of years).

Example (based on IPCC methodology)

Question

Wheat crop is grown in a field of 1000 ha in the dry tropical climate region. Initially the field was conventionally tilled and high inputs of inorganic fertilizer were used. Later, the conventional tillage was replaced by no tillage and inorganic fertilizer was applied along with organic manure for the last 30 years. Calculate the change in SOC of 30 cm soil after 30 years of wheat cultivation following changed agronomic management. Initial SOC was 0.5% and bulk density (BD) is 1.3 Mg m^{-3} .

Solution

In this study SOC is 0.5%, BD is 1.3 Mg m^{-3} , and thickness of soil (T) is 30 cm. Therefore using the formula $\text{SOC}_{\text{REF}} = \text{SOC} * \text{BD} * T$

We get, $\text{SOC}_{\text{REF}} = 0.5 * 1.3 * 30 = 19.5 \text{ Mg ha}^{-1}$

Initially $F_{\text{LU}} = 0.58$, $F_{\text{MG}} = 1$, $F_{\text{I}} = 1.04$ [From Table 2]

So $\text{SOC}_{0-T} = 19.5 * 0.58 * 1 * 1.04 * 1000 = 11762.4 \text{ Mg}$ [$\text{SOC}_{0-T} = \text{SOC}_{\text{REF}} * F_{\text{LU}} * F_{\text{MG}} * A$]

$A = \text{land area} = 1000 \text{ ha}$.

Therefore initially carbon stock of the area was 11762.4 Mg.

Now $\text{SOC}_0 = 19.5 * 0.58 * 1.17 * 1.37 * 1000 = 18128.8 \text{ Mg}$ [$\text{SOC}_0 = \text{SOC}_{\text{REF}} * F_{\text{LU}} * F_{\text{MG}} * A$]

When management practices were changed, $F_{\text{LU}} = 0.58$, $F_{\text{MG}} = 1.17$, $F_{\text{I}} = 1.37$ (From Table 2)

F_{LU} remained same, since land use has not changed. The area is still under wheat cultivation.

A also remains unchanged.

Change in SOC (ΔC) = $(18128.8 - 11762.4)/30 = 212.2 \text{ Mg C yr}^{-1}$ [$\Delta C = (\text{SOC}_0 - \text{SOC}_{0-T})/T$]

It can be concluded that change in agronomic management has led to sequestration of soil organic carbon at the rate of $212.2 \text{ Mg C yr}^{-1}$.

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Preparation and Utilization of Biochar for Soil Amendment

TJ Puarakayastha

Introduction

Biochar is a carbon-rich charcoal-like substance produced by heating plant material under low oxygen conditions by a process known as pyrolysis. During pyrolysis, around 50% of the biomass carbon is converted into biochar and of the other 50%, around two-thirds can be released as useful energy. Land application of biochar is not a new concept. It traces its roots to observations made by 19th century naturalists. In recent times, biochar gained importance after the observation of black carbon in *Terra Preta* soil in the Amazonian basin of Brazil by late Wim Sombroek, a distinguished Pedologist. The radiocarbon dating studies have revealed them to originate from 500 years to 7000 years. They provide a visually compelling proof for the longevity of biochar carbon in soil.

Biochar being a highly carbonized, aromatic long chain compound is extremely resistant to decomposition by microbes in soil. This led to the concept of using biochar for long-term carbon sequestration for mitigating climate change. Nevertheless, biochar can be used as a soil amendment to improve soil health and increase crop production. In this regard, an obvious positive attribute of biochar is its nutrient value, supplied either directly by providing nutrients to plants or indirectly by improving soil quality, with consequent improvement in the efficiency of fertilizer use.

Surface chemistry and C/N ratio are the two properties which make biochar to change the behaviour of nutrients in soil. Nutrient composition and availability of biochar depend upon the nature of feedstock and the pyrolysis conditions. In the Indian context, the study has tremendous implications as India has biochar production potential of 309 million tonnes annually (equivalent to 154 Mt of

biochar carbon), the application of which might offset about 50% of carbon emissions from fossil fuels. It is a matter of concern that in the Indian state of Punjab alone, some 70-80 Mt straws of rice and wheat are burnt annually, releasing approximately 140 Mt of CO₂ into the atmosphere, in addition to methane, nitrous oxide and air pollutants (Punia *et al.*, 2008). Under this scenario, biochar offers a significant, multi-dimensional opportunity to transform large-scale agricultural waste streams from a financial and environmental liability to valuable assets.

Preparation of Biochar

Biochar is prepared by the process called “pyrolysis”. The term ‘pyrolysis’ is typically used for the bio-energy systems that capture the off-gases emitted during charring and used to produce hydrogen, syngas, bio-oils, heat or electricity and biochar is produced as a by-product. In simple terms, pyrolysis is the chemical decomposition of an organic substance by heating under complete or partial exclusion of oxygen. The pyrolysis platform which is used for the conversion of bioenergy to useful substances requires a huge infrastructure, and therefore its initial establishment cost is high. A low-cost pyrolysis klin is an alternative to the huge pyrolysis platform for the production of biochar. The former technology does not provide to capture energy and other useful co-products. But because of low investment, the low-cost pyrolysis klin could be popularised in the rural India. The kiln is entirely above ground and following steps are required for its construction (Figure 1):

1. Place a flat, level concrete pad
2. Construct a round firebrick enclosure for a 200-litre barrel that leaves approximately 10 cm of space around the barrel, about 30 cm underneath the barrel, and 10 cm above the barrel. In other words, the enclosure should be some 40-50 cm taller than the barrel. Also, the enclosure should have an opening at the bottom to add firewood under the barrel.
3. Weld a frame that fits inside the firebrick enclosure and raises the barrel about 30 cm from the base.
4. Modify the barrel as necessary, depending on the type, so that feedstock can be added. Seal the barrel, and yet allow off-gases to escape. Practically speaking, if the barrel is open on the top, a plate with a minimum 4 mm thickness is needed to cover it. The plate could be weighted with firebrick.



Figure 1. Design of low-cost pyrolysis kiln

The barrels have threaded openings in the top. Now to cut a hole in the top, about 20 cm in diameter, from where feedstock and char could be loaded and unloaded. This hole is then closed with sheet and metal screws using a heat-resistant gasket. It is preferred to open the top barrel with a plate, with the addition of small hole, about 50 cm, with a 2" pipe fitting welded to it. This allows directing the off-gases to an afterburner easily, and avoids the problems that may develop with sheet metal screws and gaskets.

5. It is cautioned not to light the contents of the barrel on fire, from the top or bottom. The barrel/retort is sealed, more or less airtight, with only a small opening to allow the off-gases to escape. The flow of off-gases will not allow entry of air into the retort. The barrel is placed inside the firebrick enclosure, the temperature probes are inserted into the barrel through small 3-mm holes; the barrel is loaded with biomass, sealed (with the weighted plate for instance), and then a small fire is started under the barrel.

6. Temperature is controlled relatively easily by limiting the size of the fire under the barrel (within the firebrick enclosure). During the first hour or so, moisture is primarily driven out of the feedstock and very little, if any, pyrolysis occurs. At least this is the case when wood is used as a feedstock. Temperature inside the barrel is continuously monitored by digital temperature probes inserted at three different heights of the barrel. Temperatures don't rise into the target zone during this initial period. Then suddenly, temperature starts rising up and goes up to about 400 °C, especially at the top measure point. Since heat rises, the pyrolysis zone tends to move from the top to the bottom of the barrel. Towards the end of the process, temperature rises to 400 °C at the bottom measurement point. Maintain the temperature at 400 °C for about half an hour and then stop external heating and allow the barrel to cool down to ambient temperature. If there is a leakage and allow it to cool for a longer period. During the process, the biochar is converted to ash. Alternatively, two hours after external heating is stopped, the lid of the barrel is opened and water is added from the top to extinguish the left-over heat inside the biochar. Next day, the biochar is removed from the barrel and kept in open for drying under the sun. After drying, the biochar is stored in gunny bags for its further application to soil.

Facetes of Biochar

Four complementary and often synergistic objectives may motivate biochar applications for environmental management: soil improvement (for improved productivity as well as reduced pollution); waste management; climate change mitigation; and energy production (Figure 2), which individually or in combination must have a social or financial benefit or both.

Nature of Biochar

Biochar is defined as the carbon-rich product produced by thermal decomposition of organic material under limited supply of oxygen and at relatively low temperatures (< 700 °C) (Lehmann and Joseph, 2009). Biochars with large amounts of carbon in polycondensed aromatic structures are obtained by pyrolyzing organic feedstocks at high temperatures (> 700 °C), but also have fewer ion exchange functional groups due to dehydration and decarboxylation, potentially limiting its usefulness in retaining soil nutrients. Moreover, biochars

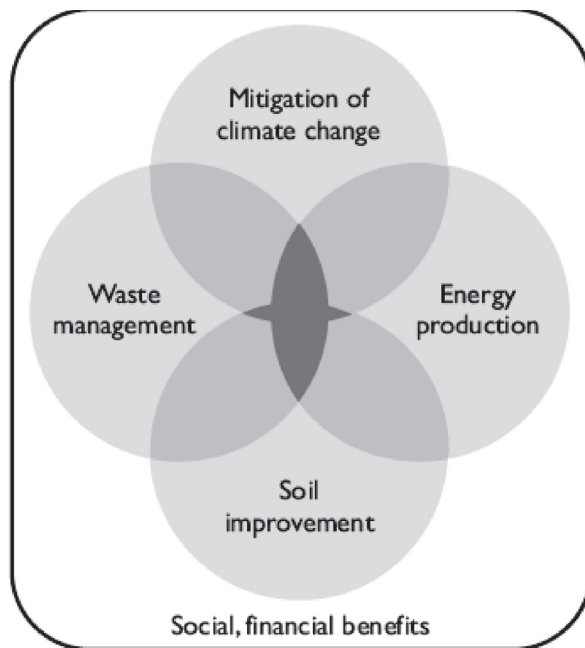


Figure 2. Motivation for applying biochar technology (Lehmann and Joseph, 2009)

produced at lower pyrolysis temperatures ($< 700\text{ }^{\circ}\text{C}$) have more diversified organic character, including aliphatic and cellulose type structures. Experimental evidence shows that a range of different functional groups exist on the surfaces of the graphene sheets. Hydrogen, O, N, P and S are incorporated in the aromatic rings as heteroatoms. The presence of heteroatoms results in surface chemical heterogeneity caused mainly by differences in the electronegativity of the heteroatoms relative to the C atoms (Brennan *et al.*, 2001). Groups such as OH, NH_2 , OR or $\text{O}(\text{C}=\text{O})\text{R}$ are classified as electron donors (due to the presence of electrons), whereas $(\text{C}=\text{O})\text{OH}$, $(\text{C}=\text{O})\text{H}$ or NO_2 groups are classified as electron acceptors (due to the presence of empty orbitals). The quantities of the carboxyl groups, the combined acidity of the 3 functional groups (carboxyls + lactones + phenols), total surface acidity (carboxyls + lactones + phenols + additional acidic species), and surface basicity of the biochars have been presented in Table 1. The total and combined surface acidity of the 3 functional groups was higher in the low-temperature than in the high-temperature biochars; the reverse trend was found for the total surface basicity of biochars. The number of carboxyl groups

Table 1. Oxygenated acidic and basic functional groups (mmole/g C) (mean $\pm$ S.E.) of biochars, after removing soluble salts and carbonates, as determined by Boehm titrations

Feed stock	Pyrolysis temperature (°C)	Carboxyl	Carboxyl+lact one+phenolic	Total acidity	Total basicity
<i>E. saligna</i> wood	400, activated	0.83 $\pm$ 0.11	2.68 $\pm$ 0.14	5.71 $\pm$ 0.76	0.60 $\pm$ 0.16
	550, activated	0.20 $\pm$ 0.08	0.65 $\pm$ 0.15	1.58 $\pm$ 0.13	0.35 $\pm$ 0.07
	400 non-activated	0.26 $\pm$ 0.05	3.14 $\pm$ 0.09	6.07 $\pm$ 0.58	0.38 $\pm$ 0.08
	550 non-activated	0.17 $\pm$ 0.05	0.53 $\pm$ 0.17	1.49 $\pm$ 0.55	0.31 $\pm$ 0.09
<i>E. saligna</i> leaves	400, activated	0.63 $\pm$ 0.11	2.67 $\pm$ 0.17	5.34 $\pm$ 0.73	0.93 $\pm$ 0.05
	550, activated	0.24 $\pm$ 0.08	0.93 $\pm$ 0.13	2.39 $\pm$ 0.61	1.06 $\pm$ 0.11
Paper sludge	550, activated	0.43 $\pm$ 0.11	0.86 $\pm$ 0.10	3.27 $\pm$ 0.21	7.66 $\pm$ 1.66
Poultry litter	400, non-activated	0.83 $\pm$ 0.15	3.23 $\pm$ 0.14	5.10 $\pm$ 0.30	4.29 $\pm$ 0.23
	550, activated	0.26 $\pm$ 0.09	1.20 $\pm$ 0.09	1.67 $\pm$ 0.05	2.20 $\pm$ 0.10
Cow manure	400, non-activated	2.01 $\pm$ 0.24	5.15 $\pm$ 0.09	8.08 $\pm$ 0.79	6.46 $\pm$ 0.271
	550, activated	1.00 $\pm$ 0.24	2.12 $\pm$ 0.24	3.42 $\pm$ 0.40	0.28 $\pm$ 0.39
LSD ($P=0.05$)		0.39	0.42	1.52	1.54

Source: (Singh *et al.*, 2010)

decreased at higher temperature for most biochars, and the activated low-temperature wood biochar had a higher number of carboxyl groups than its non-activated counterpart. The high-temperature cow manure biochar had the highest surface basicity and the low-temperature cow manure biochar had the highest surface acidity. Overall, the papermill sludge and manure-based biochars had higher surface basicity than the eucalyptus biochars.

During thermal conversion, the mineral and C skeleton formed retains the rudimentary porosity and structure of the original material. The residual cellular structures of botanical origin that are present and identifiable in biochars from woods and coals of all ranks contribute most of the macroporosity present (Wildman and Derbyshire, 1991). Confirming this, the microscopic analysis of physically activated carbon has illustrated the presence of aligned honeycomb-like groups of pores of the order of 10 nm in diameter, most likely the carbonaceous skeleton from the biological capillary structure of the raw material (Laine *et al.*, 1991). The fundamental molecular structure of biochar creates both its surface area and porosity. The biochar structure, determined by X-ray diffraction, is

essentially amorphous in nature, but contains some local crystalline structure (Qadeer *et al.*, 1994) of highly conjugated aromatic compounds. Biochar specific surfaces, being generally higher than sand and comparable to or higher than clay, will therefore cause a net increase in the total soil-specific surface when added as an amendment. The mechanical strength of biochar is related to its solid density. Therefore, the increased molecular order of pyrolysed biomass provides it a higher mechanical strength than the biomass feedstock from which it is derived.

A higher amount of biochar is recovered at lower pyrolysis temperatures due to minimal condensation of aliphatic compounds, and lower losses of CH₄, H₂ and CO. Below 350 °C, the yield recovery was at least 50%. The yield declined to about 30% as the pyrolysis temperature was raised, up to 500 °C or 700 °C because of dehydration of hydroxyl groups and thermal degradation of ligno-cellulosic structures. The carbon recovery efficiency (biochar C/feedstock C) showed a similar pattern with mean carbon recovery ranging between 44% and 72% for the high and low temperature regimes. Increase in pyrolysis temperature from 400°C to 600°C increased the ash and fixed carbon content in biochar prepared from different C3 (rice and wheat) and C4 (maize and switch grass) residues, while it decreased moisture and volatile component of biochar (Purakayastha *et al.*, 2012). In general, the C:N ratio of biochar decreased while increase in pyrolysis temperature from 400°C to 600°C.

The ash content of biochars decreased significantly higher ashing temperatures (700 °C), especially for biochars containing minerals sensitive to high temperatures such as calcite. Increase in the ashing temperature substantially decreases the ash content of paper sludge biochar. The ash contents of biochars produced from peanut hulls, pecan shells, and switchgrass are < 10%, while biochars made from the poultry litter feedstock ranges from 24% to 52%. But, a reverse trend was observed in case of volatile matter content where with the increase in pyrolysis temperature, the volatile matter content of different biochars decreased (Purakayastha *et al.*, 2012). The volatile carbon structures of biochar include alcohols, oils, tars, acids, etc. which can be re-condensed as bio-oil. The biochar that remains is consisted mainly of C, besides some O, H, N, and ash [calcium (Ca), potassium (K)], etc.

Application of Biochar in Soil

It has been observed that the recovery of biochar is approximately 50-60% of the weight of the biomass. The size of the biochar material is reduced to 1-4" by manual crushing before application in the field. The land is tilled with tractor drawn disc. The biochar is applied on the surface of the soil and incorporated into the soil with disc or spade to a depth of about 15 cm.

Benefits of Biochar Application in Soil

Crop Productivity

It was reported that the application of biochar in soil led to a reduction in N leaching by 60% and increase in crop productivity by 38-45%, which was translated into saving of 20% in fertilizer-use and 10% savings in irrigation and seeds (Lehman *et al.*, 2003). Nevertheless, the yield increased up to 140% on poor soils under recommended fertilization (Lehmann and Rondon, 2006). A single application of 0, 8 t ha⁻¹ and 20 t ha⁻¹ of biochar to Colombian savanna Oxisol for 4 years (2003–2006), under maize-soybean rotation was studied by Major *et al.* (2010). There was no significant increase in maize grain yield in the first year, but increases of 28%, 30% and 140% were observed in subsequent years, viz. 2004,

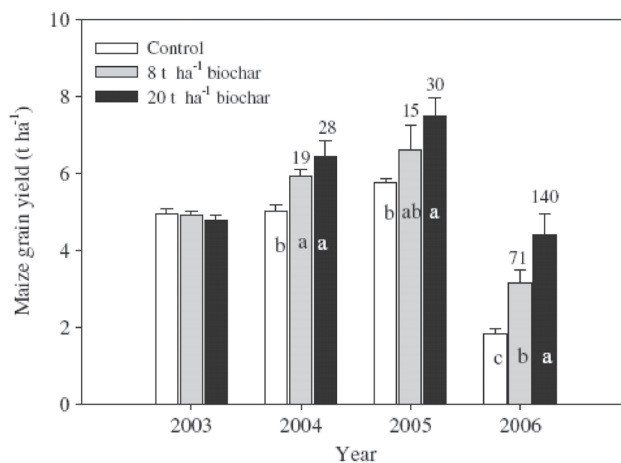


Figure 3. Maize grain yield on Colombian savanna Oxisol amended with biochar in late 2002 ($\pm$ SE, $n=3$). Numbers above bars are the percent yield increase compared to the optimally managed control, and different letters indicate significant differences between means ($p < 0.05$) within a single year (Major *et al.*, 2010)

2005 and 2006, respectively, compared to control plot. The availability of nutrients such as Ca and Mg was higher on applying biochar, and crop tissue analyses showed that Ca and Mg were limiting in this system. Soil pH increased, and exchangeable acidity showed a decreasing trend with biochar application. The higher crop yield and nutrient uptake could be attributed primarily to 77–320% more availability of Ca and Mg in the soil in which biochar was applied.

Carbon Sequestration

Pyrolysis converts trees, grasses or crop residues into biochar, with two-fold higher carbon content than ordinary biomass. Moreover, biochar locks up rapidly decomposing carbon in plant biomass in a much more durable form (Baldock and Smernik, 2002). Biochar is a lower-risk strategy than other sequestration options, in which stored carbon can be released, say, by forest fires, by converting no-tillage back to conventional tillage, or by leaks from geological carbon storage. Once biochar is incorporated into the soil, it is difficult to imagine any incident or change in practice that would cause a sudden loss of stored carbon. Plant biomass decomposes in a relatively short period of time, whereas biochar is orders of magnitudes more stable. So, given a certain amount of carbon that cycles annually through plants, half of it can be taken out of its natural cycle and sequestered in a much slower biochar cycle. By withdrawing organic carbon from the cycle of photosynthesis and decomposition, biochar sequestration directly removes carbon dioxide from the atmosphere and stores it in a much more durable form in soil. Therefore, locking carbon up in soil makes more sense than storing it in plants and trees that eventually decompose (Lehmann, 2007). It was reported that the biochar carbon is very stable in soil as very less amount of C was lost from different C3 and C4 biochar (Purakayastha *et al.*, 2012).

Nutrient Cycling

Biochar can play a key role in nutrient cycling, potentially affecting nitrogen retention when applied to soils. Experiments were conducted to investigate the adsorption properties of bamboo charcoal (BC) and its influence on nitrogen retention at different soil depths using multilayered soil columns (Ding *et al.*, 2010). Results revealed that BC could adsorb ammonium ions predominantly by the cation exchange process. The concentration of ammonium nitrogen ($\text{NH}_4^+\text{-N}$) in the leachate of soil columns showed significant differences at different depths after application of ammonium chloride to the columns, depending on whether

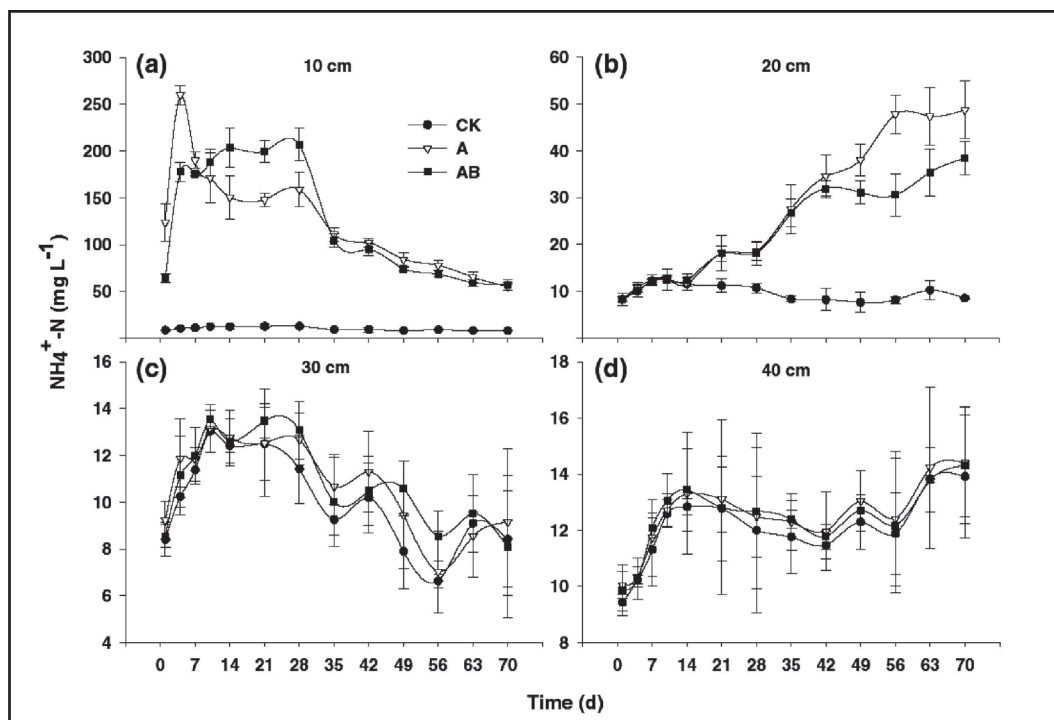


Figure 4. Temporal changes in $\text{NH}_4^+\text{-N}$ concentration in the leachate of soil columns at different depths (treatments: CK: no-fertilizer; A: ammonium chloride at 400 kg N ha⁻¹; AB: ammonium chloride at 400 kg N ha⁻¹ + 0.5% bamboo charcoal) (Ding *et al.*, 2010)

BC had been added or not. Addition of 0.5% BC to the surface soil layer retarded the downward transport of $\text{NH}_4^+\text{-N}$ in the 70-day experiment, as indicated by the measurements made during the first 7 days at 10 cm, and later, in the experimental period at 20 cm depth (Figure 4). In addition, application of BC reduced the overall cumulative losses of $\text{NH}_4^+\text{-N}$ via leaching at 20 cm depth by 15.2%. The study suggested that BC could be used as a potential nutrient-retaining additive to increase the utilization-efficiency of chemical fertilizers. The application of biochar is reported to enhance significantly the availability of K in soil (Purakayastha *et al.*, 2012)

Physical Properties of Soil

Biochar, a co-product of thermochemical conversion of lignocellulosic materials, may be used as a soil amendment to enhance the sustainability of biomass

harvesting. The physical properties of acid sulphate soil of West Kalimantan improved due to the application of organic soil amendments like rice husk, rice husk biochar, rice husk ash, rice straw, etc. Bulk density (BD) decreased from 1.24 Mg m^{-3} in the control experiment to 1.14 Mg m^{-3} in the rice straw treated soil, as reported by Masulili *et al.* (2010). The BD of soil treated with rice husk biochar was 1.17 Mg m^{-3} , which was not significantly different from that of soil treated with the rice straw soil amendment. The decrease in soil bulk density with application of organic soil amendment was due to the incorporation of a soil which had a relatively high BD (1.24 Mg m^{-3}) and lower density of organic soil amendment (less than 1.00 Mg m^{-3}). Masulili *et al.* (2010) have also reported that rice husk biochar could substitute the liming materials which are used to increase pH of the acidic soils. The decrease in concentration of exchangeable-Al and soluble-Fe in rice husk biochar and other organic soil amendments is undoubtedly due to the increase of CEC in the soil. For the P nutrient, however, this increase could have also been as a result of increase in soil pH due to rice husk ash or rice husk biochar application.

Microbial Activities in Soil

The porous structure of biochar along with its high internal surface area and ability to adsorb soluble organic matter, gases and inorganic nutrients are likely to provide a highly suitable habitat for the microbes to colonize, grow and reproduce, particularly for bacteria, actinomycetes and arbuscular mycorrhizal fungi. Some members of these groups may preferentially colonize on biochar surfaces, depending upon the physical and chemical characteristics of different biochars, discussed below. The pore space of pyrolysed biomass increases during charring by several thousand-fold and is related to charring temperature and feedstock materials. It is estimated that surface area of different biochars range from $10 \text{ m}^2 \text{ g}^{-1}$ to several hundred square metres per gram, which provides a significantly increased surface area for microbial colonization. Depending upon the size of a given pore, different microbes will or will not have access to internal spaces. The biochar pores could also act as a refuge site or microhabitat for colonizing microbes, where they are protected from grazing by their natural predators (Warnock *et al.*, 2007). Experiments have suggested that biomass-derived black carbon (biochar) affects microbial populations and soil biogeochemistry. Both biochar and mycorrhizal associations, ubiquitous symbioses in terrestrial ecosystems, are potentially important in various ecosystem services provided by

soils, contributing to sustainable plant production, ecosystem restoration, and soil carbon sequestration and hence mitigation of global climate change. The mechanisms by which biochar could influence mycorrhizal abundance and/or functioning are: (in decreasing order of available evidence): (a) alteration in physico-chemical properties of soil; (b) indirect effects on mycorrhizae through effects on other soil microbes; (c) plant–fungus signalling interference and detoxification of allelochemicals on biochar; and (d) provision of refugia from fungal grazers. Microbial activities measured in terms of dehydrogenase activity (DHA) in soil depend upon the type of feedstock used for biochar preparation. The DHA significantly increased due to C4 (maize stover and switchgrass) biochar while it decreased due to application of C3 (rice and wheat) biochar (Purakayastha *et al.*, 2012)

Immobilization of Heavy Metal in Soil

Contamination of soil interstitial waters by labile heavy metals, such as Cu(II), Cd(II), and Ni(II), is a worldwide concern. Carbonaceous materials such as char and activated carbon have received considerable attention in recent years as a soil amendment for both sequestering heavy metal contaminants and releasing essential nutrients like sulphur. Currently, information is lacking on how aging impacts the integrity of biochars as soil amendment for both agricultural and environmental remediation purposes. Uchimiya *et al.* (2010) studied the effect of ageing or oxidation of Pecan shell-derived biochar at 450 °C for 4 hr under air flow rates of 100 mL, 800 mL and 2000 mL. For Cd(II) and Ni(II), 10% or higher amendment was necessary for the activated carbons to enhance the immobilization of metal ions. The increase in sorption capacity with the oxidation state was attributed to the formation of oxygen-containing surface functional groups that are able to form complex with metal ions.

Economics of Biochar Production and Application

Small-scale systems for biomass inputs of 50-1000 kg/hour can be used on farms, while large units say up to of 8000 kg/hour can be operated by large industries. Biochar can be produced on a large-scale through centralized system (industrial dynamic biochar production system) and on a small-scale in the farms through a decentralized system (biochar stove and biochar kiln). Carbon zero experimental biochar kiln is a simple closed retort kiln built with insulated firebricks. Its enclosure

is designed for a 200 litre steel barrel as a retort. The barrel is filled with split wood or other biomass feedstock, covered, and heated from below with a separate wood fire until it reaches pyrolysis temperatures (over 320 °C). Different aspects of decentralized system of biochar production (Lee and Khan, 2011) given below:

- Needs initial investment of US \$200-500
- Household units
- Produces mainly biochar
- Functions as a stove or grill
- Used based on personal need

The initial cost of construction of low cost pyrolysis klin as shown in Figure 1 is around Rupees twenty thousand. The cost of production of biochar by using wood as energy source is estimated around Rupees fifteen per kilogram. The cost will reduce further if the benefits of biochar are assessed by yield enhancement and carbon sequestration.

The economic costs and benefits of fast and slow pyrolysis, as well as the associated products, considered are:

- Feedstock production and collection,
- Value lost by feedstock removal in terms of altered nutrients and tillage on fields from which crop residue was harvested,
- Feedstock hauling,
- Feedstock storage and pre-processing,
- Feedstock processing,
- Pyrolysis operation,
- Energy sales,
- Biochar hauling and application,
- Biochar-induced cropping system gains, and
- GHG offsets.

Conclusions

In India the production potential of biochar is huge as over 300 million tonnes of crop residues are generated annually. The prime benefits of biochar are hidden in enhancing the carbon sequestration potential of soil. The other associated benefits

of biochar are centred on enhancing the physical, chemical and biological properties of the soil. Biochar could be used for improving water holding capacity, soil quality, and nutrient retention (e.g., reducing nitrogen leaching), and thus, increases crop yield depending on biochar characteristics, type of soil and crop management. Biochar is a potential cost-effective catalyst for several industries, producing biochar-based fertilizers and bioenergy generation. These multifaceted uses can be achieved if low cost production technologies are made available at the grassroot level. The fertilizer function of biochar is highly supported by the increased water retention and CEC of the soils caused by the huge surface area of the biochars. Rice husk biochar could be used as a substitute for the liming materials to improve the quality of acid sulphate soils. To popularize biochar application among the Indian farmers, it is extremely essential to develop specialized biochar stove for producing biochar from crop residues and trap the energy thus evolved for household-use.

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Isotopic Studies for Assessing Organic Matter Turnover in Soil

Ranjan Bhattacharyya

Introduction

Carbon (C) has 15 known isotopes, from ^8C to ^{22}C , two of which (^{12}C and ^{13}C) are stable. The longest-lived radioisotope is ^{14}C with a half-life of 5,700 years (Cerling *et al.*, 1989). It is the only radioisotope found in nature, and its trace quantities are formed cosmogenically by the reaction $^{14}\text{N} + ^1_0\text{n} \rightarrow ^{14}\text{C} + ^1_1\text{H}$. All other radioisotopes of carbon have half-life of less than half-hour; and most of them have a half-life of less than a minute. $^{13}_6\text{C}$ is a stable nuclide (Cerling *et al.*, 1991). The relative abundance of natural carbon is 1.108 atom per cent. It is used as a tracer in studies on reaction mechanisms and carbon metabolism; but now is often replaced by ^{14}C , unless double labelling is required. ^{13}C is used when use of a non-radioactive isotope is essential. In this chapter, the principles for determination of $^{13}\text{C}/^{12}\text{C}$ are described and the uses of natural abundance of ^{13}C are discussed.

Detection of $^{13}\text{C}/^{12}\text{C}$ by NMR Spectroscopy

Because of its nuclear spin properties, isotope responds to a resonant-radio frequency (RF) signal. The absorption and emission of the RF signal by the nuclei can be monitored and detected using nuclear magnetic resonance spectroscopy, commonly known as NMR spectroscopy (Golchin *et al.*, 1995). It is a technique that provides information on the identity and number of atoms adjacent to other atoms in the said molecule, thereby giving clues to the structure of an organic molecule. Since ^{12}C has a zero spin, it does not give an NMR signal, and since only 1% of the atoms in a molecule are of ^{13}C , it is unlikely that carbon-carbon coupling is seen. To obtain a ^{13}C NMR spectrum, it may take from a couple of minutes to hours because many scans have to be summed together in order to have results distinguishable from the background noise.

Detection of $^{13}\text{C}/^{12}\text{C}$ by Mass Spectrometry

The mass spectrum of an organic compound usually contains a small peak of one mass unit greater than the apparent molecular ion peak (M). It is known as the M+1 peak and originates due to the presence of ^{13}C atoms. A molecule containing one carbon atom will be expected to have one M+1 peak of approximately 1.1% of the size of the M peak, as 1.1% of the carbon atoms will be ^{13}C rather than ^{12}C (Piper *et al.*, 2008). Similarly, a molecule containing two carbon atoms will be expected to have M+1 peak of approximately 2.2% of the size of the M peak, as there is double of the previous likelihood that a molecule will contain a ^{13}C atom. In the following formula the result should be rounded to the nearest integer:

$$C = \frac{100Y}{1.1X} \quad \dots(1)$$

where, C = Number of C atoms, X = Amplitude of the M ion peak, and Y = Amplitude of the M+1 ion peak

^{13}C -enriched compounds are used in the research on metabolic processes by mass spectrometry. Such compounds are safe because they are non-radioactive. In addition, ^{13}C is used to quantify proteins (quantitative proteomics). One important application is in 'stable isotope labelling with amino acids in cell culture' (SILAC). ^{13}C -enriched compounds are used in medical diagnostic tests such as the urea breath test. In these tests analysis is usually done of the ratio of ^{13}C to ^{12}C by isotope ratio mass spectrometry.

The ratio of ^{13}C to ^{12}C is slightly higher in plants employing C_4 carbon fixation than in plants employing C_3 carbon fixation (Ehleringer, 1993). Since different isotope ratios for the two kinds of plants propagate through the food chain, it is possible to determine if the principal diet of a human being or other animal consists primarily of C_3 plants or C_4 plants by measuring the isotopic signature of their collagen and other tissues. Deliberate increase in the proportion of ^{13}C in diet is the concept of i-food, a proposed way to increase longevity.

Use of ^{13}C Isotope in Soil Organic Matter Turnover and Carbon Stabilization Studies

Due to differential uptake in plants as well as marine carbonates of ^{13}C , it is possible to use these isotopic signatures in earth science. In aqueous geochemistry, by

analyzing the $\delta^{13}\text{C}$ values of surface water and groundwater, the source of water can be identified. It is due to the fact that atmospheric, carbonate and plant derived $\delta^{13}\text{C}$ values differ with respect to Pee Dee Belemnite (PDB) standard (Knoller *et al.*, 2005).

To calculate $\delta^{13}\text{C}$, Equation (2) is used:

$$\delta^{13}\text{C}_{\text{sample}} = \left(\frac{{}^{13}\text{C}/{}^{12}\text{C}_{\text{sample}}}{{}^{13}\text{C}/{}^{12}\text{C}_{\text{PDB}}} - 1 \right) 1000 \quad \dots(2)$$

The quantities of different isotopes can be measured by mass spectrometry and compared to a standard; the result (e.g., the delta of $^{13}\text{C} = \delta^{13}\text{C}$) is expressed as parts per thousand (‰). The stable carbon isotopes in carbon dioxide are utilized differentially by plants during photosynthesis. Grasses in temperate environments (barley, rice, wheat, rye oats, sunflower, potato, tomatoes, peanuts, cotton, sugarbeet, and most trees and their nuts/fruits, roses and Kentucky bluegrass) follow a C_3 photosynthetic pathway that yield $\delta^{13}\text{C}$ values averaging to about -26.5‰ , as fixation of CO_2 to phosphoglycerate occurs with the assistance of the enzyme RUBISCO (ribulosebiphosphate carboxylase) that discriminates heavily against $^{13}\text{CO}_2$. Grasses in hot arid environments (maize in particular, but also millet, sorghum, sugarcane and crabgrass) follow a C_4 photosynthetic pathway (that initially fixes CO_2 into 4-C malate or aspartate, catalyzed by the enzyme phosphoenol pyruvate carboxylase) that produces $\delta^{13}\text{C}$ values averaging to about -12.5‰ , as the enzyme discriminates much less against $^{13}\text{CO}_2$ (Farquhar *et al.*, 1989). Thus, the average difference in $\delta^{13}\text{C}$ values between C_3 and C_4 plants is nearly 14‰.

In the agro-ecosystems, soil organic carbon (SOC) has at least two origins: one is the remains of the previous native vegetation and the other is the remains of crop and decomposition of residues. Where vegetation has changed from plants with C_3 photosynthetic pathway to C_4 pathway or vice versa, changes in the natural abundance of ^{13}C in soil organic matter (SOM) over time can be used to identify the sources of organic C in soil and to determine the turnover rate of SOM (Wedin *et al.*, 1995). For instance, large areas of C_3 forest have been replaced with C_4 pasture or cropland. Changes in the $\delta^{13}\text{C}$ values of SOC in these areas reflect SOM turnover rate, and provide insights regarding the role of land-use

systems on the global C cycle (Bernoux *et al.*, 1998). Thus, theoretically the ^{13}C value of SOM should be identical to the existing vegetation at a site if:

- The existing vegetation has remained unchanged for a period of time equal to that of the oldest carbon in the soil profile
- The $\delta^{13}\text{C}$ value of atmospheric CO_2 has remained constant through time, and
- No fractionation of C isotopes has taken place in the soil as a result of either decomposition processes or differential preservation of plant biochemical properties.

If assumptions 2 and 3 hold true and there is a difference in the $\delta^{13}\text{C}$ values between the soil and the vegetation, then in all likelihood, there has been some degree of compositional change in C_3/C_4 biomass in the community. Therefore, given the limits imposed by the turnover rates of SOM, it is possible to determine whether or not a change in the relative proportion of C_3 and C_4 plants has occurred by measuring the carbon isotope composition of the current plant community and SOM (Nadelhoffer and Fry, 1988).

Determination of Delta ^{13}C in Soil Samples

Delta ^{13}C signature can be measured on a 5 g subsample, which should be pulverized using a Ball mill. If the soil pH is above 7, carbonates should be removed using acid fumigation (Harris *et al.*, 2001). The $\delta^{13}\text{C}$ signature of the original soil substrate can be measured on soil samples from the field (that is under the same management practices as the study site before the initiation of this experiment) adjacent to the experimental plots can be taken. The average $\delta^{13}\text{C}$ signature of the maize biomass can be measured (standard value: -12‰). The isotopic analyses carried out by Equation (3) are expressed in ‰ values:

$$\delta^{13}\text{C} = [(R_{\text{sam}}/R_{\text{std}})-1] * 1000 \quad \dots(3)$$

where, $R_{\text{sam}} = ^{13}\text{C}/^{12}\text{C}$ ratio of the sample, and $R_{\text{std}} = ^{13}\text{C}/^{12}\text{C}$ ratio of the working standard. Urea and soil with $\delta^{13}\text{C}$ values of -18.2‰ and -17.6‰ , respectively, serve as working standards.

The fraction of SOC derived from corn/any C_4 -plant can be calculated by Equation (4):

$$\delta m = f * \delta a + (1-f) \delta b \quad \dots(4)$$

where, δm is the current $\delta^{13}\text{C}$ in the SOC, f is the fraction of SOC from corn/any other C_4 -plant, δa is the $\delta^{13}\text{C}$ from corn residue, and δb is the initial $\delta^{13}\text{C}$. The corn/ C_4 -plant derived SOC (Mg/ha) is the product of ' f ' and the measured SOC. The remaining is relic SOC.

Another Way of Calculation

Amounts of native and maize/ C_4 -plant-derived C can also be calculated according to the method of Cerri *et al.* (1985). The $\delta^{13}\text{C}$ values of the SOM are used to calculate the proportion of new C (f_{new} , i.e. the C derived from the present maize vegetation) and of native C ($f_{\text{native}} = 1 - f_{\text{new}}$, i.e. the C derived from the native plots), by using the mass balance Equation (5):

$$f_{\text{new}} = (d_{\text{new}} - d_{\text{native}}) / (d_{\text{veg}} - d_{\text{native}}) \quad \dots(5)$$

where, δ_{new} is the $\delta^{13}\text{C}$ of the SOM of the field site, δ_{native} is the $\delta^{13}\text{C}$ of the SOM of the remaining plots similar to the native vegetation/initial $\delta^{13}\text{C}$, and δ_{veg} is the $\delta^{13}\text{C}$ of the maize.

Determination of ^{13}C Natural Abundance in Soil C Pools for C Stabilization Studies

For a C_3 - C_3 cycle or C_4 - C_3 cycle, stability of functional C pools can be determined using the ^{13}C natural abundance technique (Datta, 1998; Doane *et al.*, 2003; Schulz *et al.*, 2011). About 70 mg of bulk soil and any soil fraction (like hot water extractable-C, particulate organic matter-C, etc.) should be weighed into tin capsules for combustion to CO_2 at 950 °C in an elemental analyzer (Lichter *et al.*, 2008). Then, $\delta^{13}\text{C}$ analysis can be carried out with a IRMS. The standard defining the $^{13}\text{C}/^{12}\text{C}$ isotope scale is Vienna Pee Dee Belemnite (VPDB). To normalize the raw data (application of corrections including offset and scale factors), a two-point calibration should be used, with two well-defined reference materials (working standards) that appropriately cover the expected δ -range of the samples. A linear regression of the consensual and measured $\delta^{13}\text{C}$ values of the two working standards should be carried out following Knoller *et al.* (2005):

$$\delta^{13}\text{C}_{\text{consensual}} - \text{VPDB} = m \delta^{13}\text{C}_{\text{measured}} + b \quad \dots(6)$$

which yields the parameters m (slope) and b (y-intercept).

The regression parameters obtained are applied to all measured raw data. The normalization of the $\delta^{13}\text{C}$ raw data from the elemental analyzer can be conducted using two reference materials from the IAEA (IAEA-CH6 and IAEA-CH7). Isotope ratios (δ) can then be calculated for each soil fraction as well as bulk soil.

Uses of ^{13}C as a Natural Tracer

By using the conventional techniques, neither it is possible to quantify the fluxes of losses of humus from soil with native vegetation, nor the input of organic matter from crop residues to analyze soil C. The use of isotopic techniques, associating ^{13}C or ^{14}C permits labelling of the different substrates and then submit to the decomposing activity of the microbial biomass. These techniques have significantly contributed to the understanding of the recycling of organic matter incorporated into the soil, taking into consideration the factors such as, soil texture, humidity, nature of the substrate, etc., besides helping in estimating the activity and quantification of the microbial population.

Isotopic techniques that use ^{13}C as a natural tracer are the safe way of quantifying the turnover of SOM. Carbon dynamics in the course of organic matter transports, laterally downslopes in catenas or vertically with changing soil profile morphology, are assessed preferentially on the basis of stable isotope, especially ^{13}C measurements. Slight deviations in $\delta^{13}\text{C}$ values occur due to C-dynamics in soil. These deviations compared with the PDB standard are very helpful in the identification of soil dynamic processes.

Advantages of Using ^{13}C Isotope

1. ^{13}C isotopic composition can serve as a label and can be transmitted to other trophic levels and other ecosystems (Datta, 1998).
2. With awareness about the effects of environmental factors on metabolic processes leading to ecosystem-level values of ^{13}C composition, we have a potentially powerful tool for making quantitative inferences about the climate regimes and paleoecological processes.
3. Isotopic ratios often integrate physiological processes over long time periods, thereby providing time-integrated quantitative estimates of energy derivation.

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